Muon Neutrino and Antineutrino Oscillations

Alexander Himmel
Caltech
for the MINOS Collaboration

Fermilab Joint Experimental-Theoretical Seminar, June 14th 2010

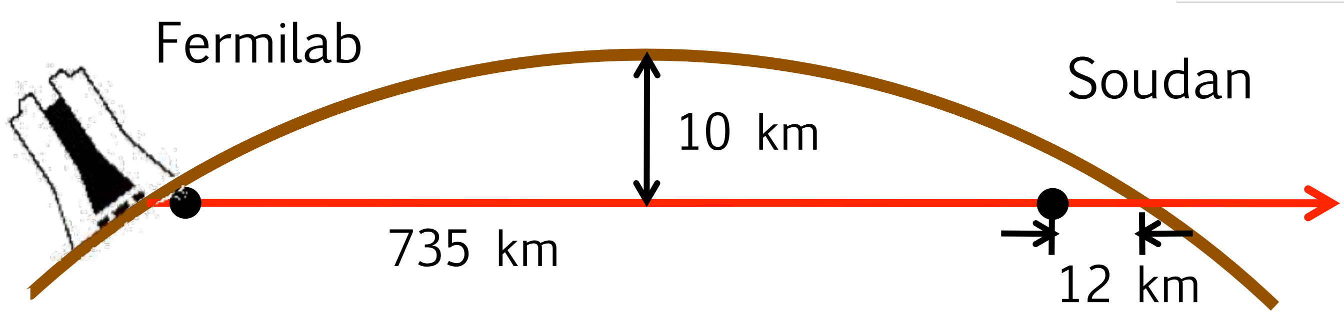
Introduction

- What is MINOS?
- Neutrino Physics
  - Oscillation Basics
  - MINOS Physics
- The Experiment
  - NuMI neutrino beam
  - MINOS detectors
- The Analyses
  - Neutrinos and Antineutrinos
- The Results

Argonne · Athens · Benedictine · Brookhaven · Caltech · Cambridge · Campinas · Fermilab · Harvard · Holy Cross · IIT Indiana · Iowa State · Lebedev · Livermore Minnesota-Twin Cities · Minnesota-Duluth· Otterbein · Oxford Pittsburgh · Rutherford · Sao Paulo · South Carolina Stanford · Sussex · Texas A&M · Texas-Austin · Tufts · UCL Warsaw · William & Mary

What is MINOS?

- Three components:
  - **NuMI** high-intensity neutrino beam
  - **Near Detector** at Fermilab
  - **Far Detector** in Soudan, MN
- Measure oscillations by looking for disappearance between the detectors
- Detectors are magnetized – unique among oscillation experiments



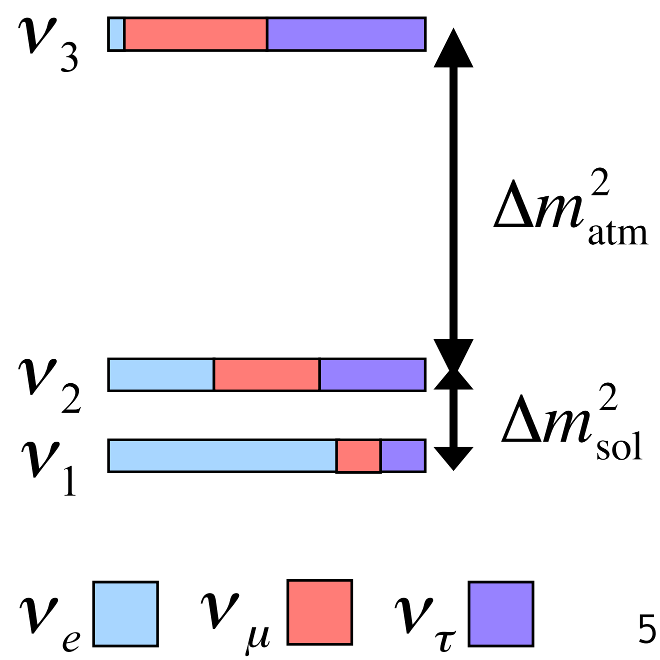
Neutrino Physics

- Oscillation Basics
- MINOS Physics

Neutrino Masses and Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \overbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\text{Solar, Reactor}} \overbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}^{\text{Mixed Sector}} \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{\text{Atmospheric, Accelerator}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- With three active neutrinos there are two independent mass splittings:
  - $\Delta m^2_{\mathrm{sol}} \approx \Delta m^2_{21} \approx 8.0 \times 10^{-5}\ \mathrm{eV}^2$
  - $\Delta m^2_{\mathrm{atm}} \approx \Delta m^2_{32} \approx 2.4 \times 10^{-3}\ \mathrm{eV}^2$
- MINOS is sensitive to the larger of the mass splittings and θ_{23}

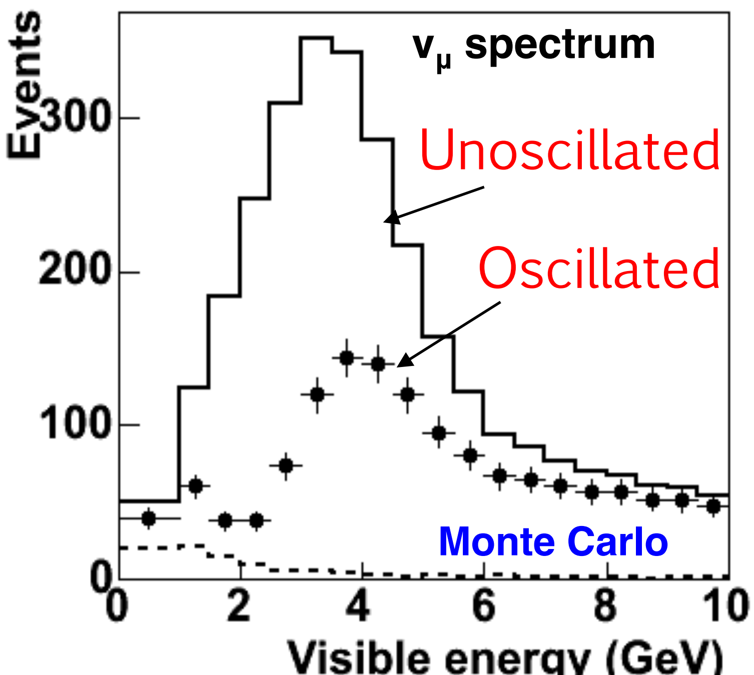


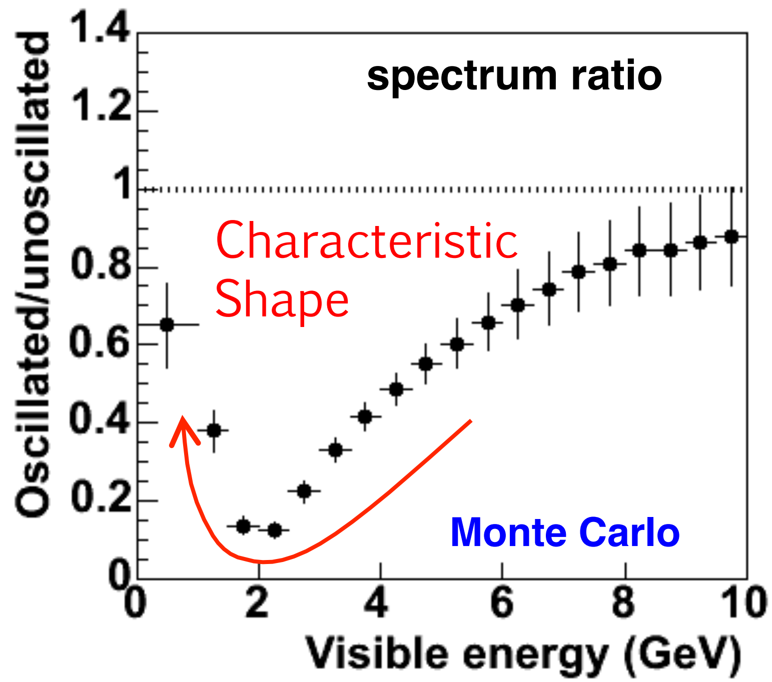
Measuring Oscillations

$$P\left(\nu_{\mu} \rightarrow \nu_{\mu}\right) = 1 - \sin^2\left(2\theta_{23}\right)\sin^2\left(1.27\Delta m^2_{atm}\frac{L}{E}\right)$$

Monte Carlo

$\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35\times10^{-3}\ eV^2$



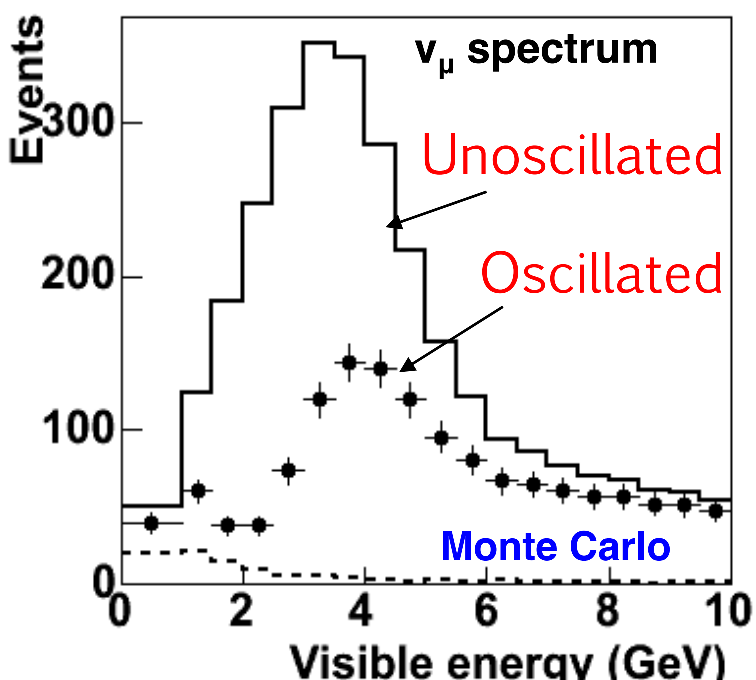


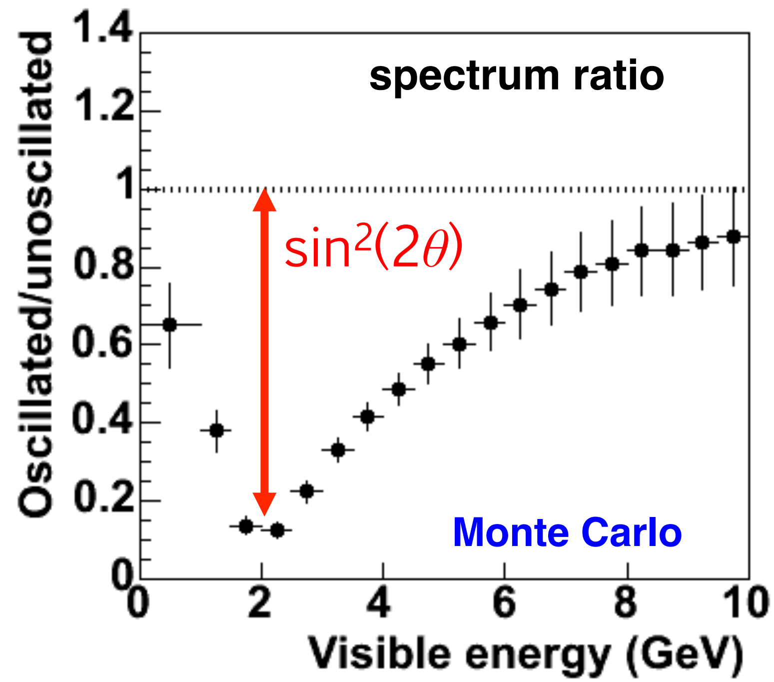
Measuring Oscillations

$$P(\nu_\mu \to \nu_\mu) = 1 - \boxed{\sin^2(2\theta_{23})}\sin^2\left(1.27\Delta m^2_{atm}\frac{L}{E}\right)$$

Monte Carlo

$\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35\text{x}10^{-3}\ \text{eV}^2$



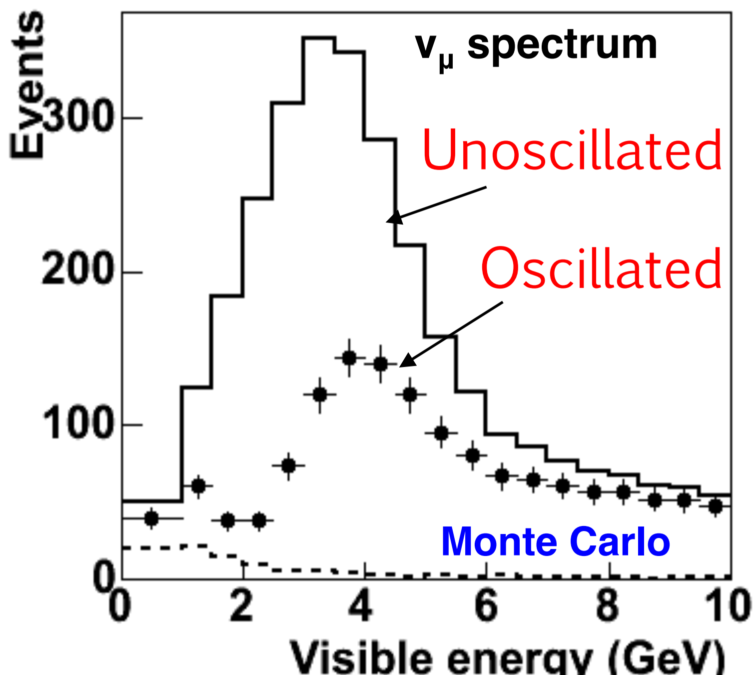


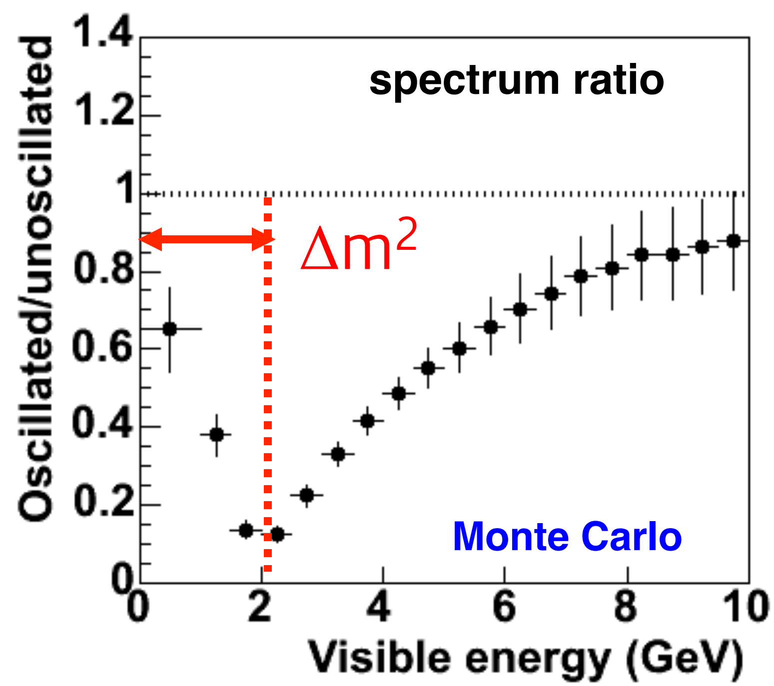
Measuring Oscillations

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\boxed{\Delta m^2_{atm}}\frac{L}{E}\right)$$

Monte Carlo

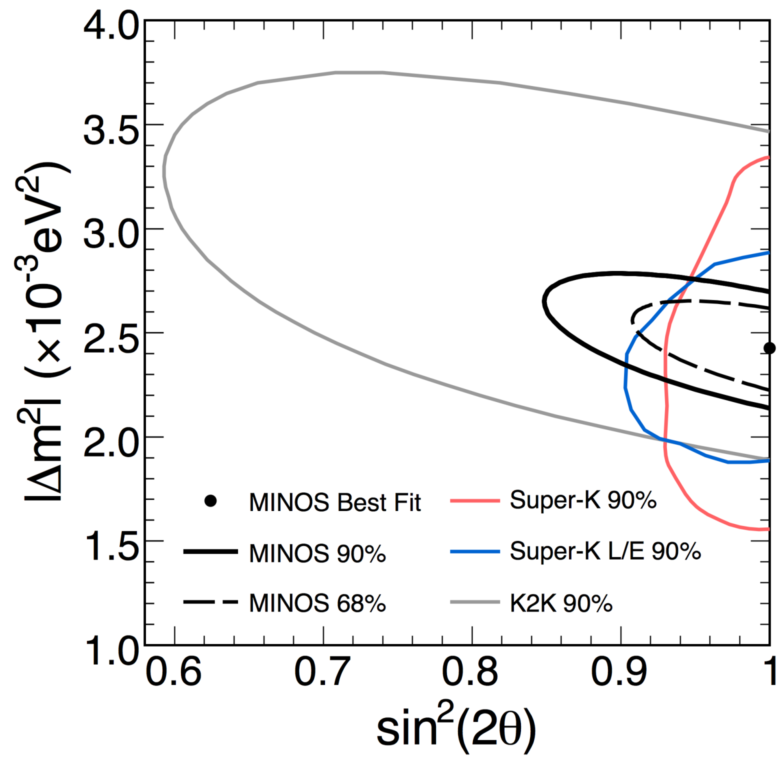
$\sin^2 2\theta = 1.0, \ \Delta m^2 = 3.35\mathrm{x}10^{-3}\ \mathrm{eV}^2$





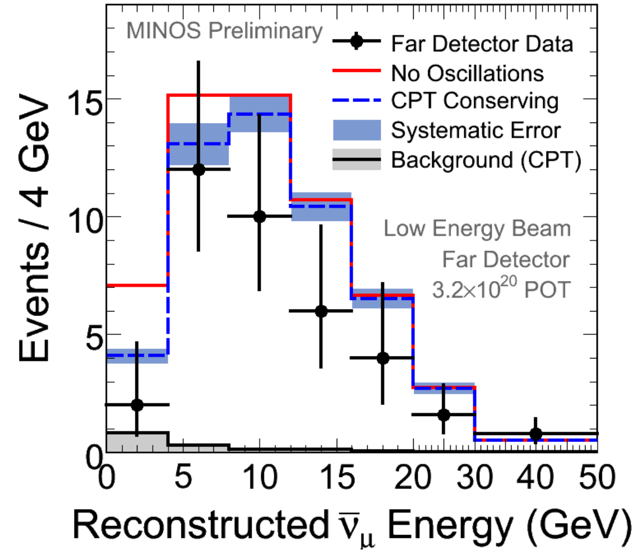
MINOS Physics

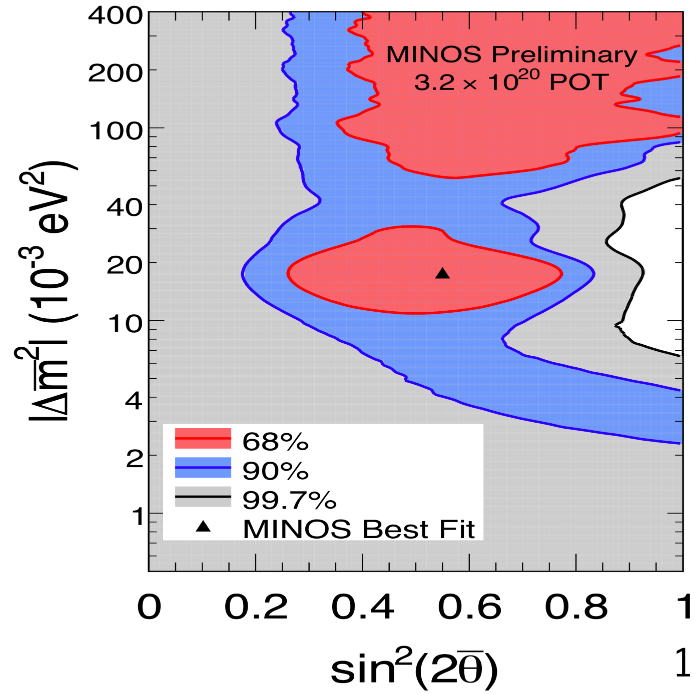
- Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
- Measurements of $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Search for sterile ν, CPT/Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector



MINOS Physics

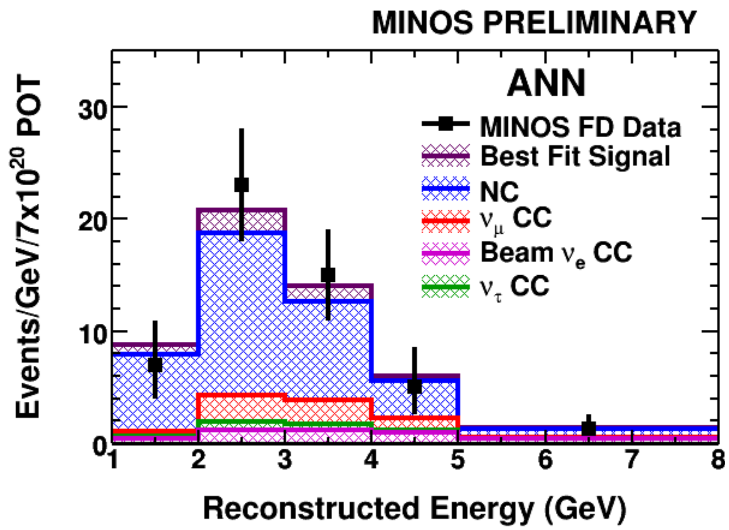
- Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
- Measurements of $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Search for sterile ν, CPT/Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector

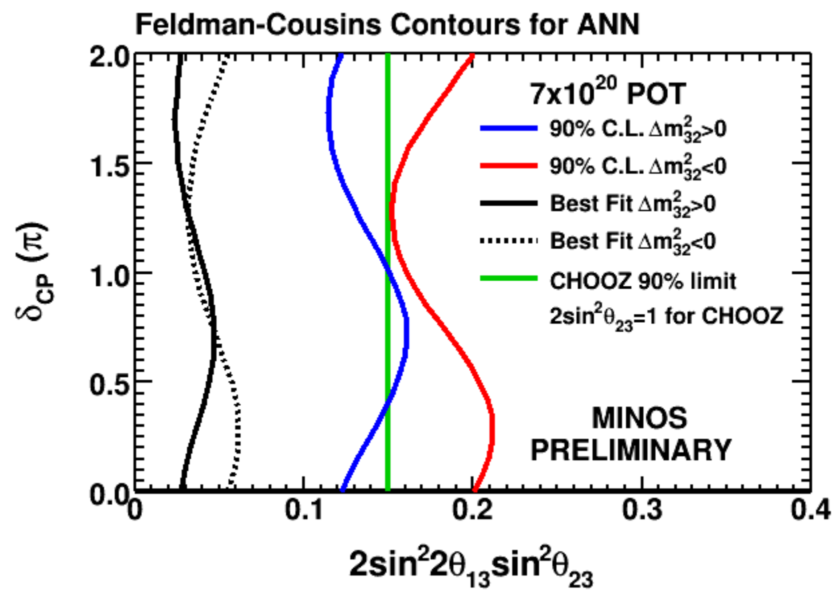




MINOS Physics

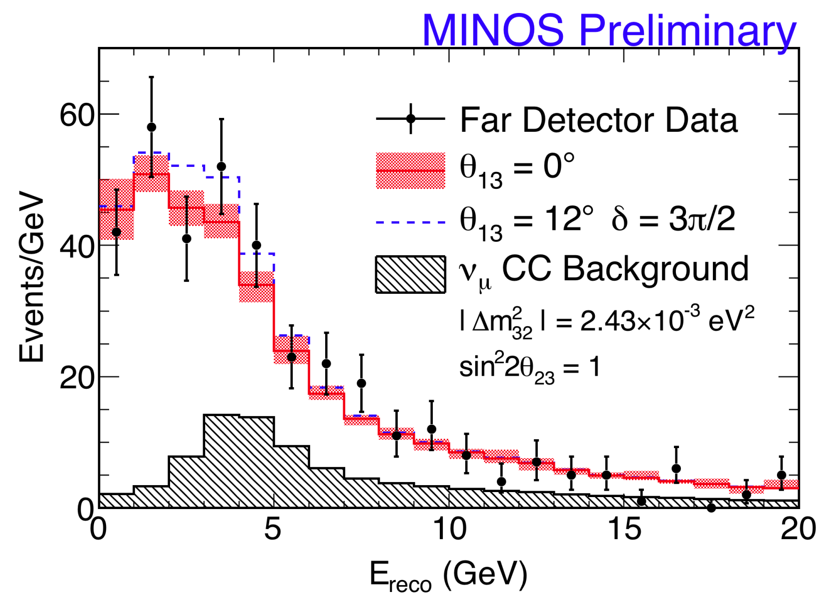
- Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
- Measurements of $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Search for sterile ν, CPT/Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector





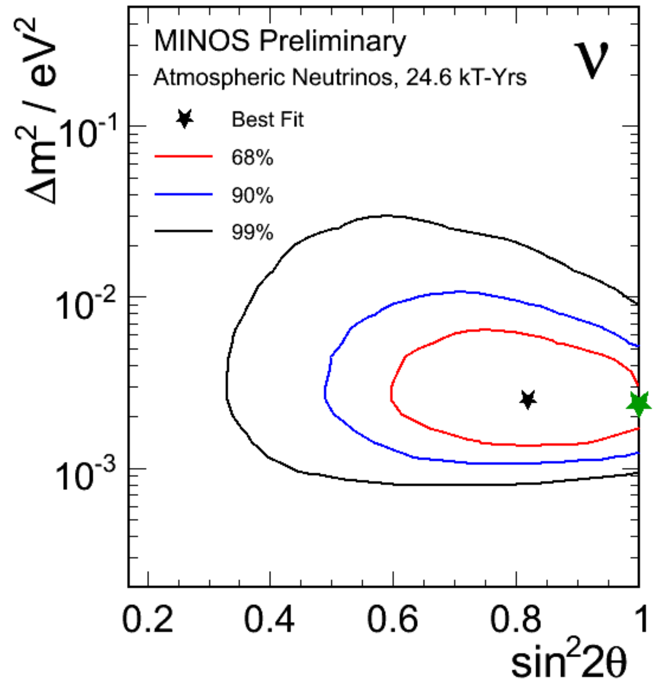
MINOS Physics

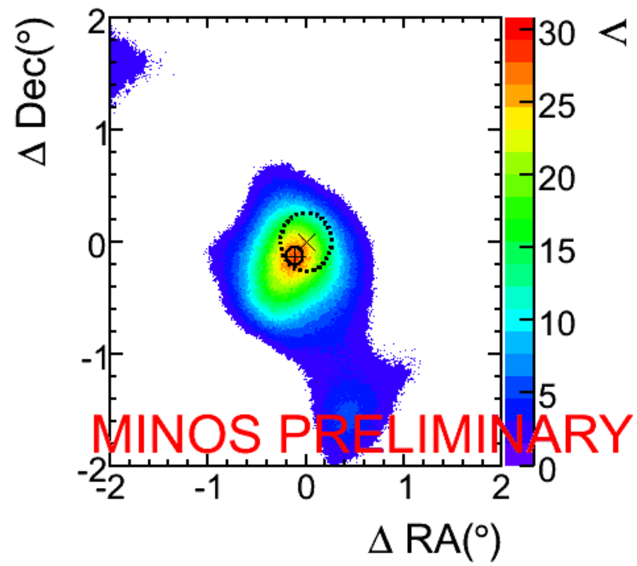
- Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
- Measurements of $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Search for sterile ν, CPT/Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector



MINOS Physics

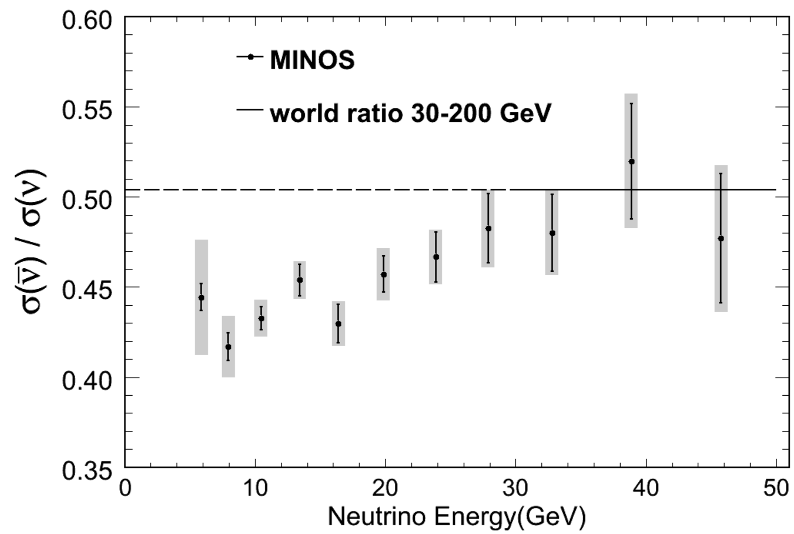
- Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
- Measurements of $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Search for sterile ν, CPT/Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector





MINOS Physics

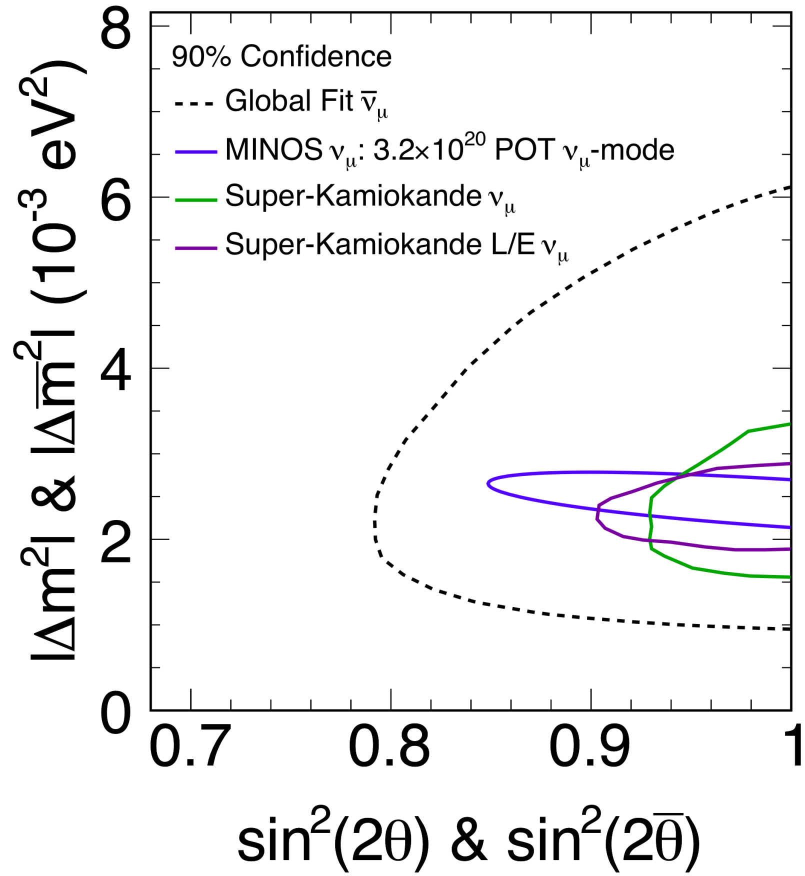
- Measurements of $|\Delta m^2_{atm}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance
- Measurements of $|\Delta \overline{m}^2_{atm}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations via ν_e appearance
- Search for sterile ν, CPT/Lorentz violation
- Atmospheric neutrino and cosmic ray physics
- Study ν interactions and cross sections in Near Detector



Why study ν_μ and $\bar{\nu}_\mu$?

$$P(\nu_\mu \rightarrow \nu_\mu) \stackrel{?}{=} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$$

- Antineutrino parameters are less precisely known.
  - No direct precision measurements
  - MINOS is the only oscillation experiment that can do event-by-event separation



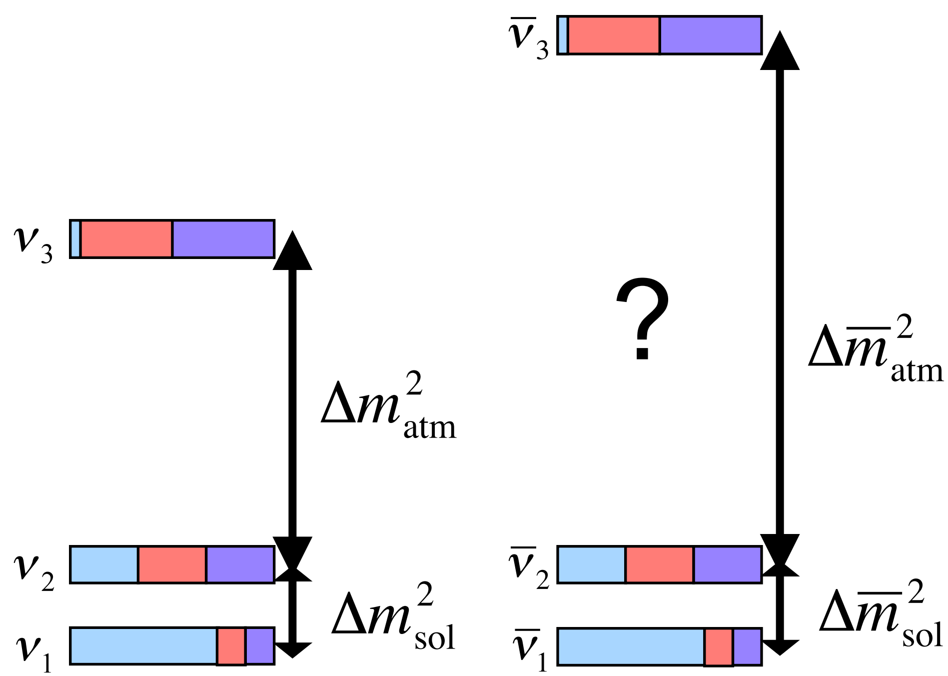
- Differences may imply new physics in the neutrino sector manifested as a difference in the effective mass-splitting.

P. Adamson, et. al, Phys. Rev. Lett. 101:131802 (2008)
Y. Ashie, et. al., Phys. Rev. D 71:112005 (2005)
Y. Ashie, et. al., Phys. Rev. D 71:112005 (2005)
M.C. Gonzalez-Garcia & M. Maltoni, Phys. Rept. 460:1-129 (2008)

Why study ν_μ and $\bar{\nu}_\mu$?

$$P(\nu_\mu \to \nu_\mu) \stackrel{?}{=} P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$$

- Antineutrino parameters are less precisely known.
  - No direct precision measurements
  - MINOS is the only oscillation experiment that can do event-by-event separation



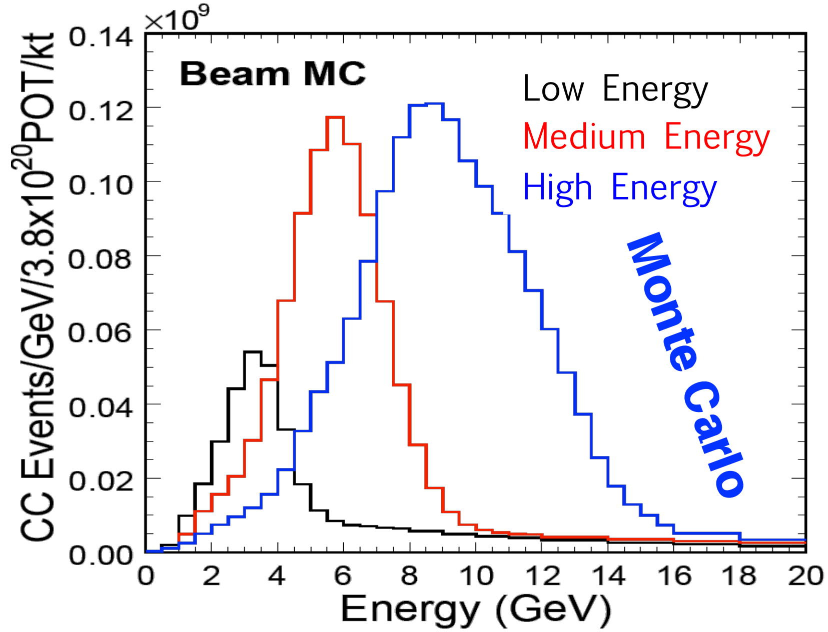
- Differences may imply new physics in the neutrino sector manifested as a difference in the effective mass-splitting.

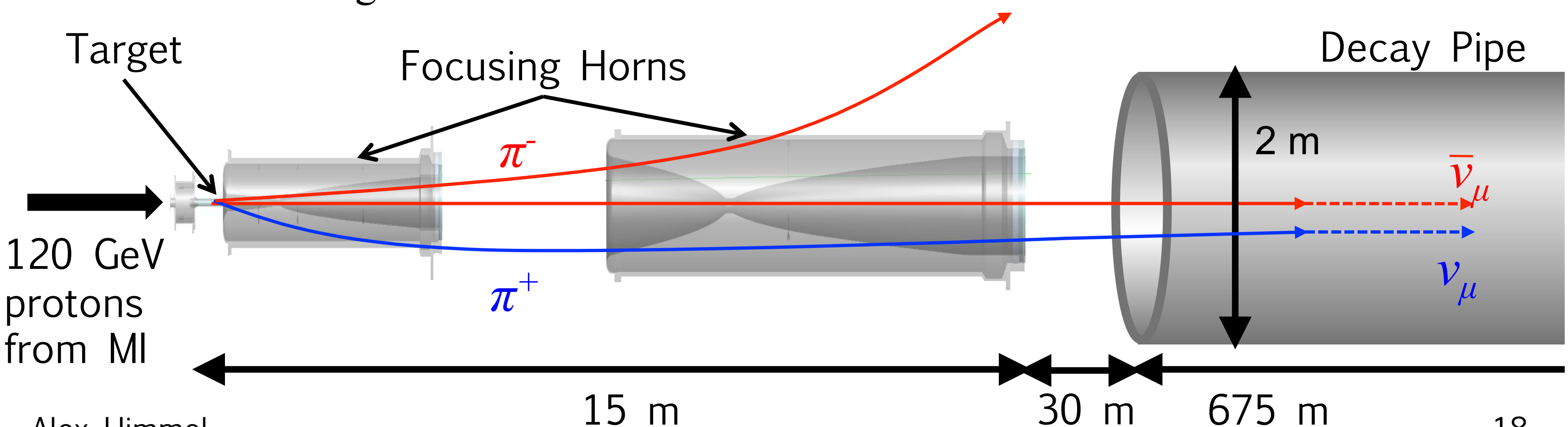
The Experiment

– NuMI neutrino beam
– MINOS detectors

The NuMI Beam

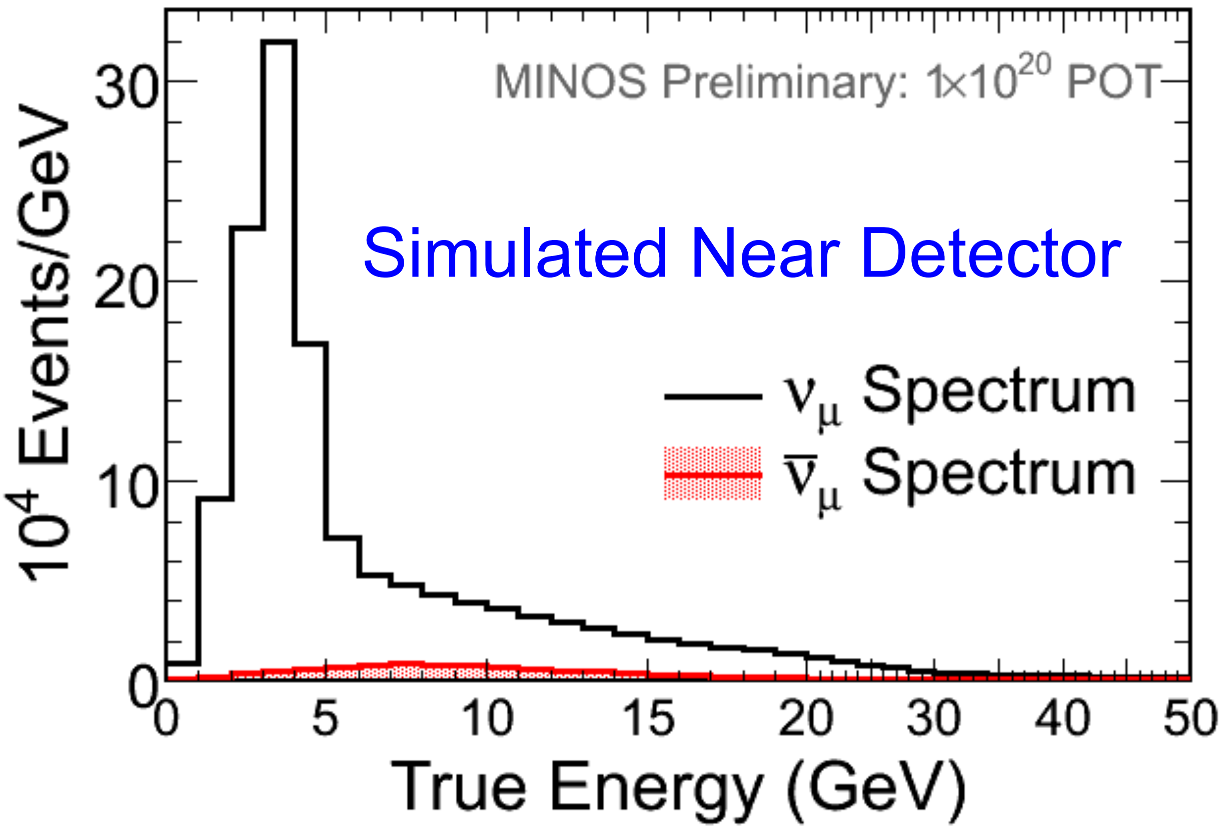
- 120 GeV protons incident on a thick, segmented graphite target
  - Producing a spray of hadrons
- Magnetic horns can focus either sign
  - Reverse direction of current
- Enhance the ν_μ flux by focusing π^+, K^+
  - And vice versa
- Adjustable energy
  - Move the target relative to the horns.



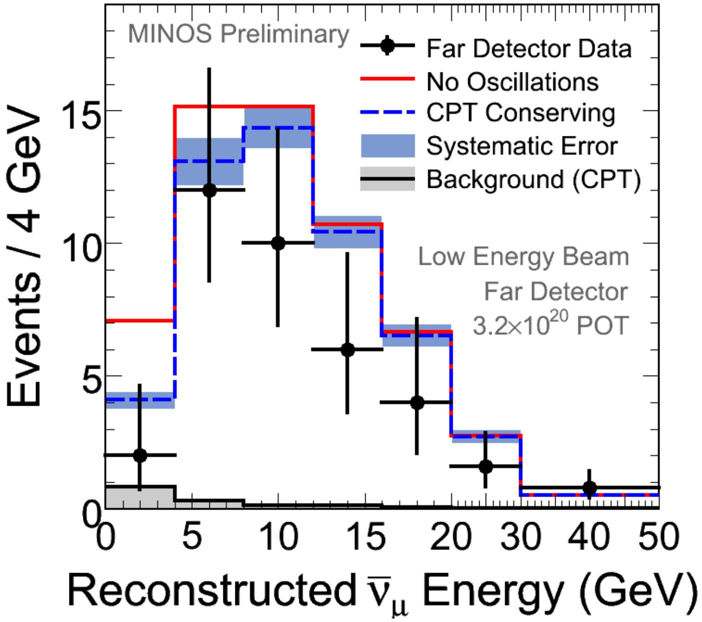


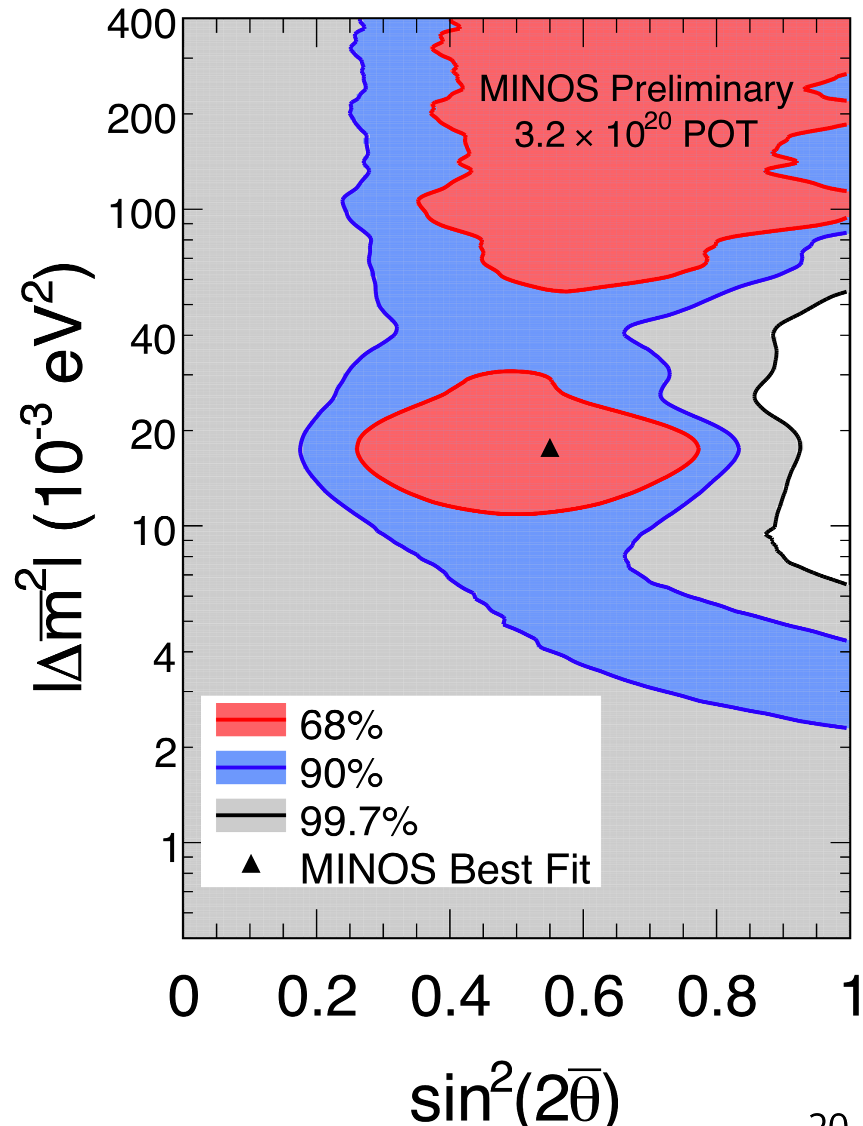
Neutrino Beam Composition

- Low energy neutrino mode
- Near detector CC interactions:
  - 91.7% ν_μ
  - 7.0% $\bar{\nu}_\mu$
  - 1.3% $\nu_e + \bar{\nu}_e$



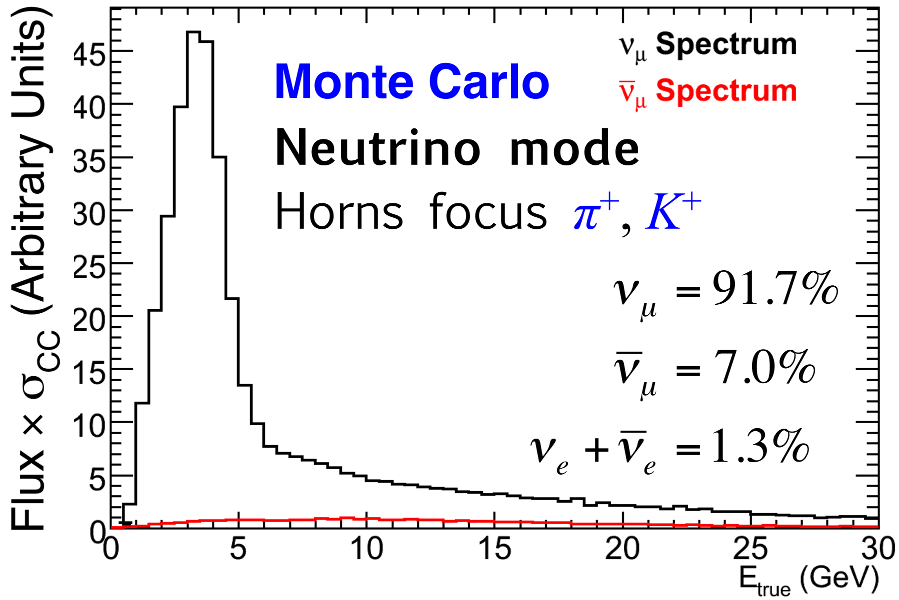
Antineutrinos in Neutrino Mode

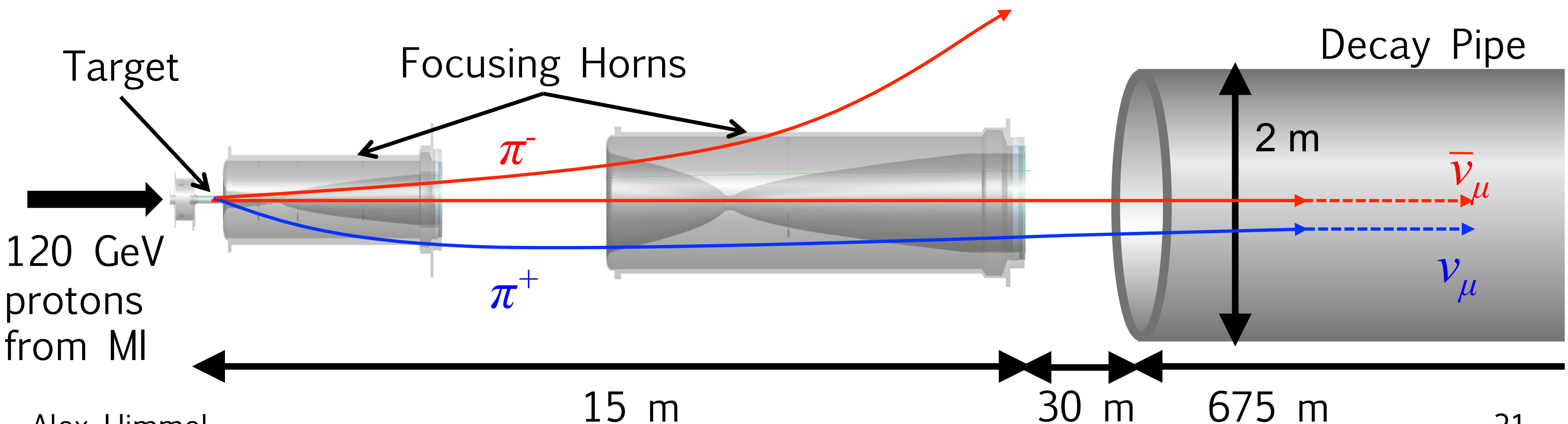




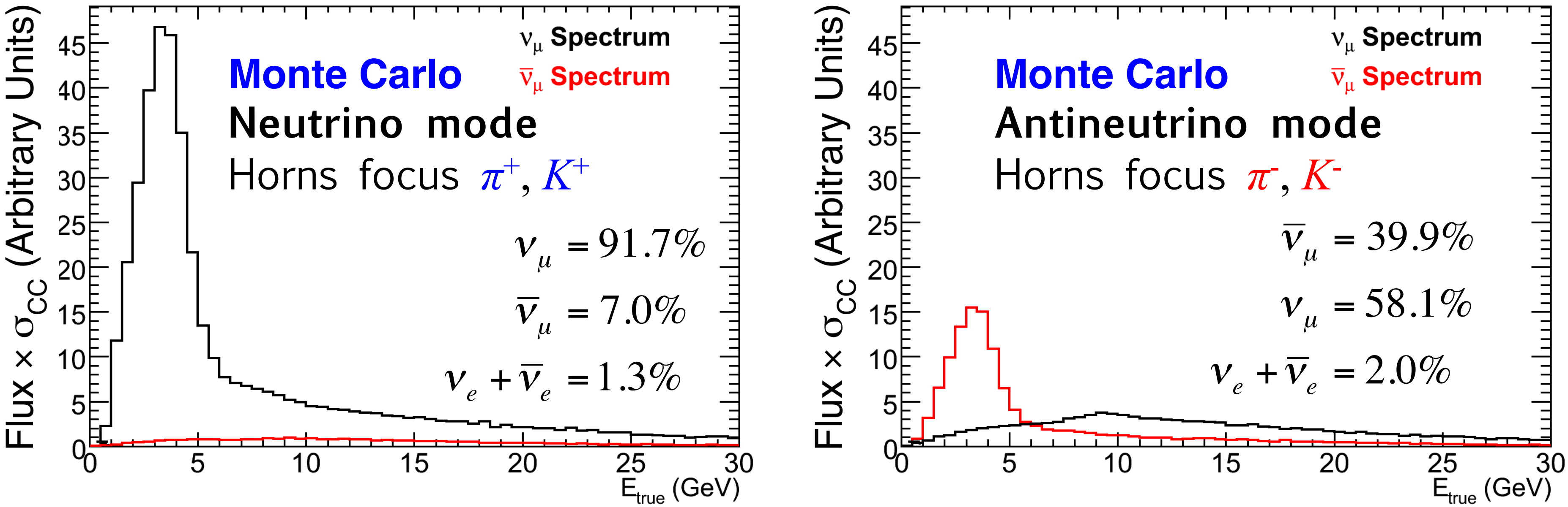
- We've already presented an analysis of the antineutrino component of the neutrino beam.
- This sample has very poor sensitivity to oscillations.

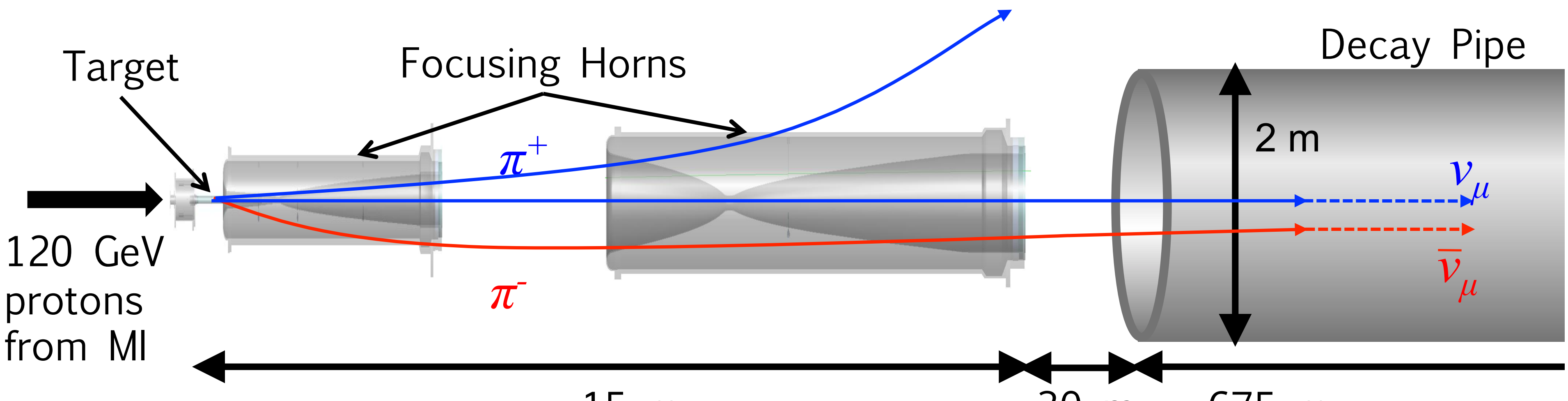
Neutrino Mode



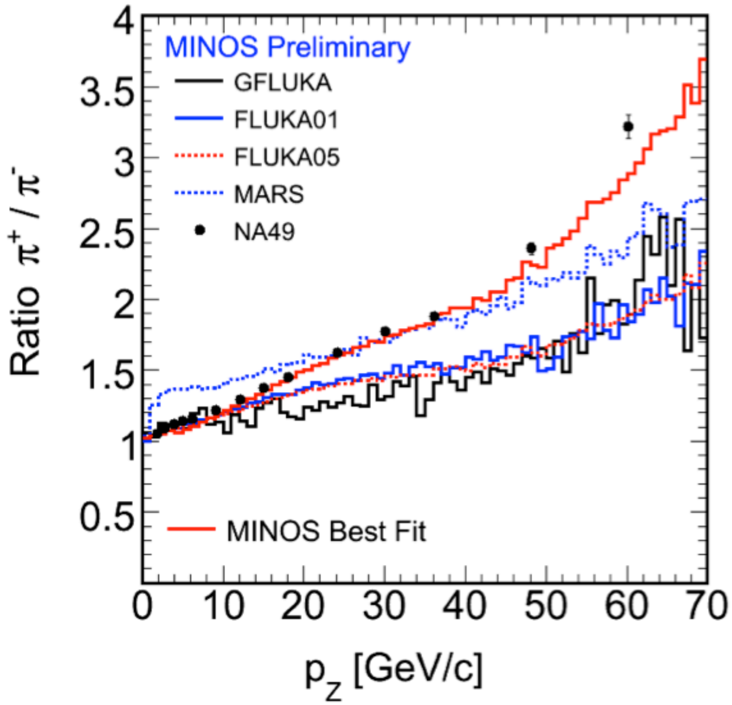


Antineutrino Mode

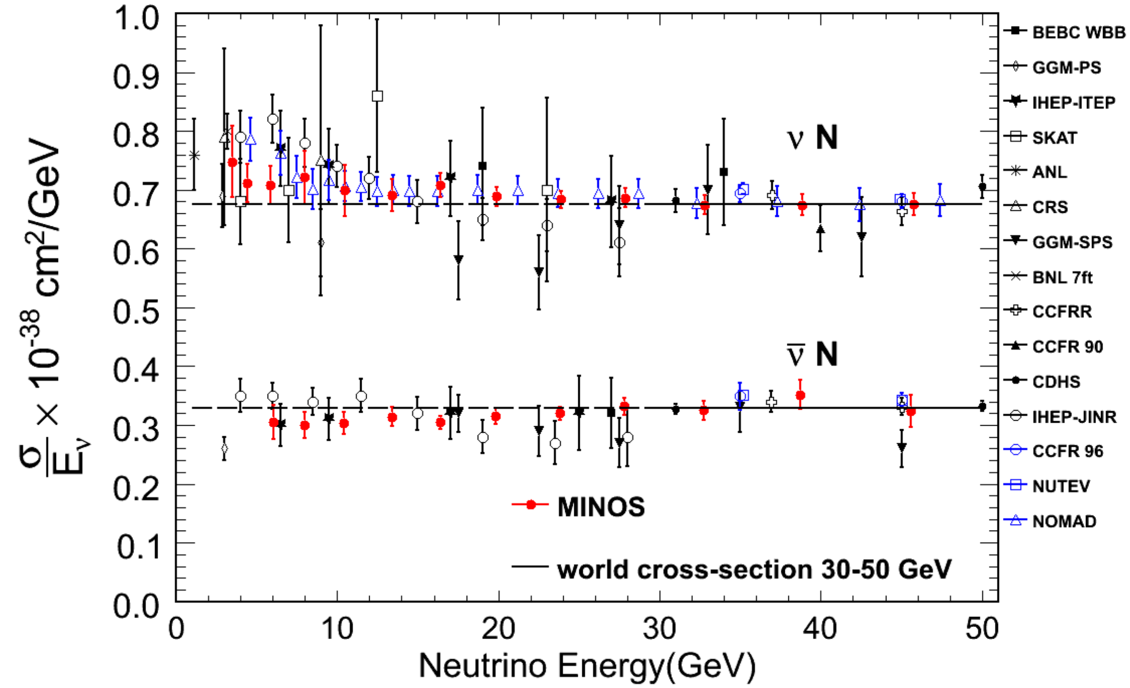




Antineutrino Cross-section



Eur. Phys. J. C 49 897 (2007)



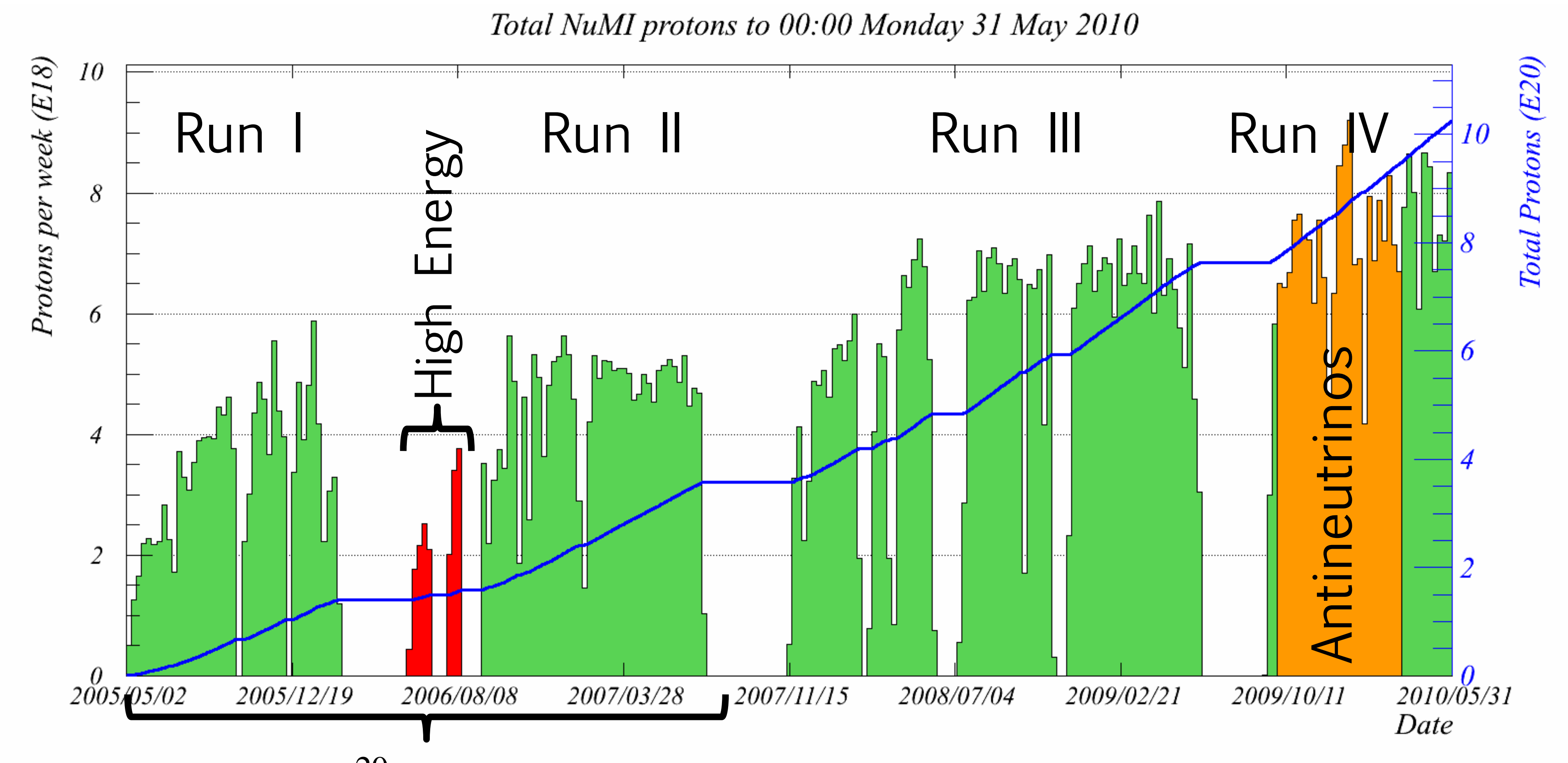
Phys. Rev. D 81 072002 (2010)

Why is the peak lower by a factor of ~3?

- x1.3 from lower π^- production
- x2.3 from lower interaction cross-section

Also explains why the high energy tail is predominantly neutrinos.

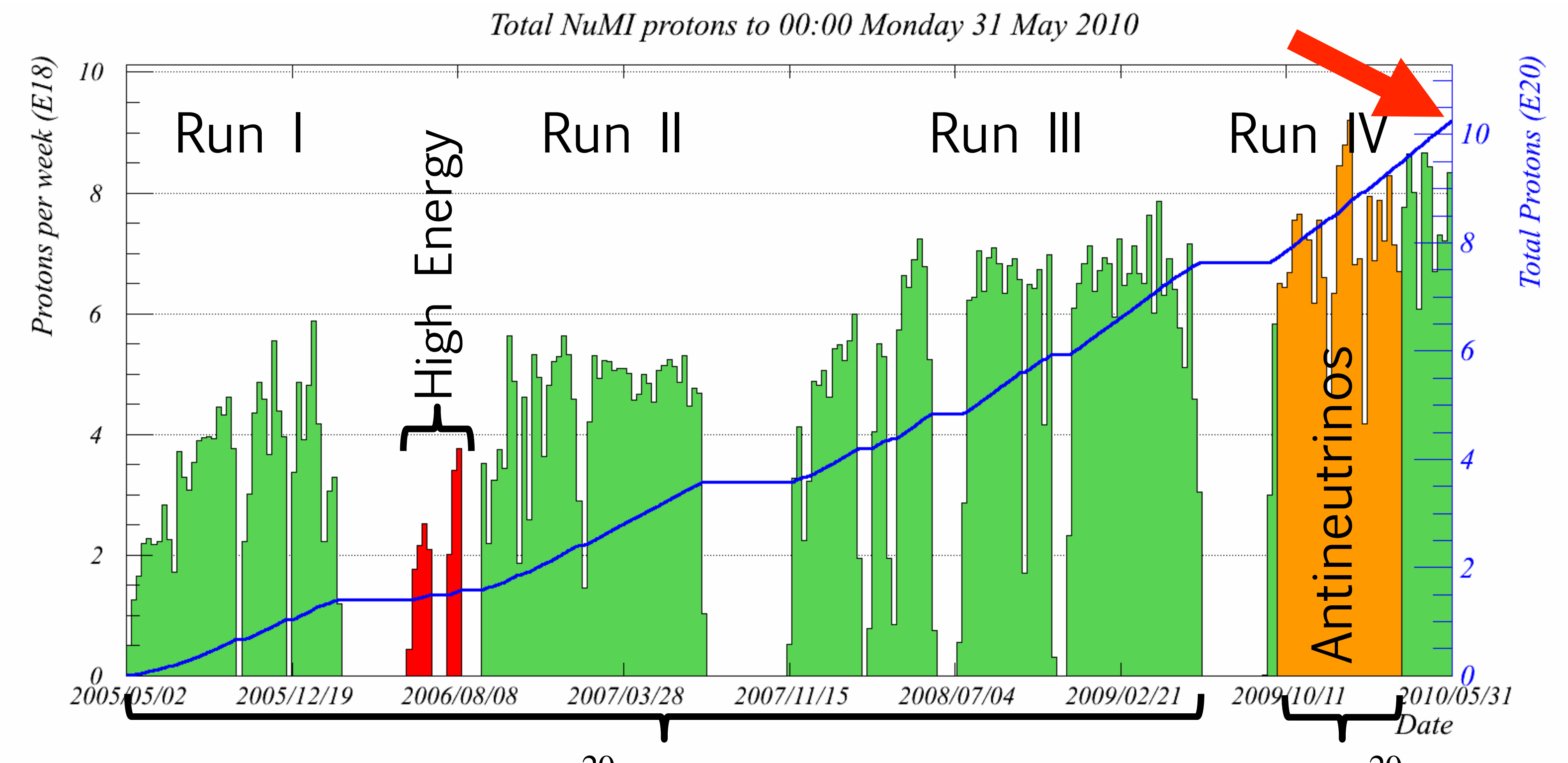
NuMI Beam Performance



3.21×10^{20} POT ν_μ mode

Previous Analyses

NuMI Beam Performance



7.24×10^{20} POT ν_μ mode

Current ν_μ Analysis

1.71×10^{20} POT

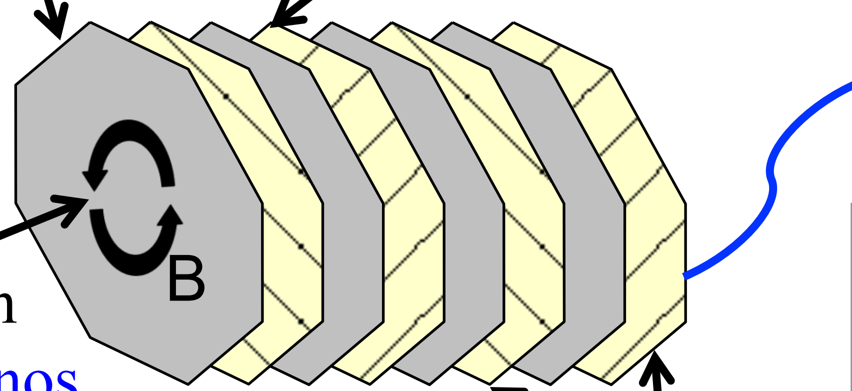
$\bar{\nu}_\mu$ mode

MINOS Detectors

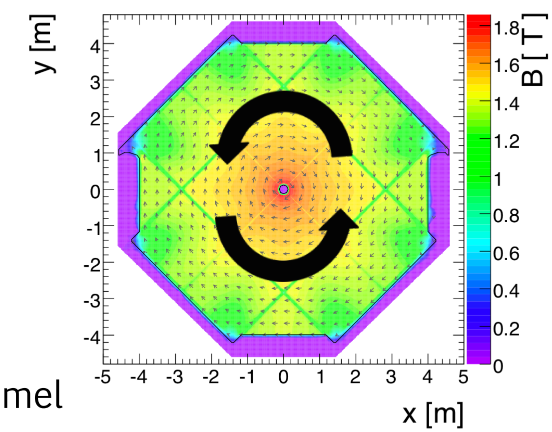
1 in thick Steel

1 cm thick, 4.1 cm wide Plastic Scintillator

Read out on wavelength-shifting fibre to multi-anode PMTs



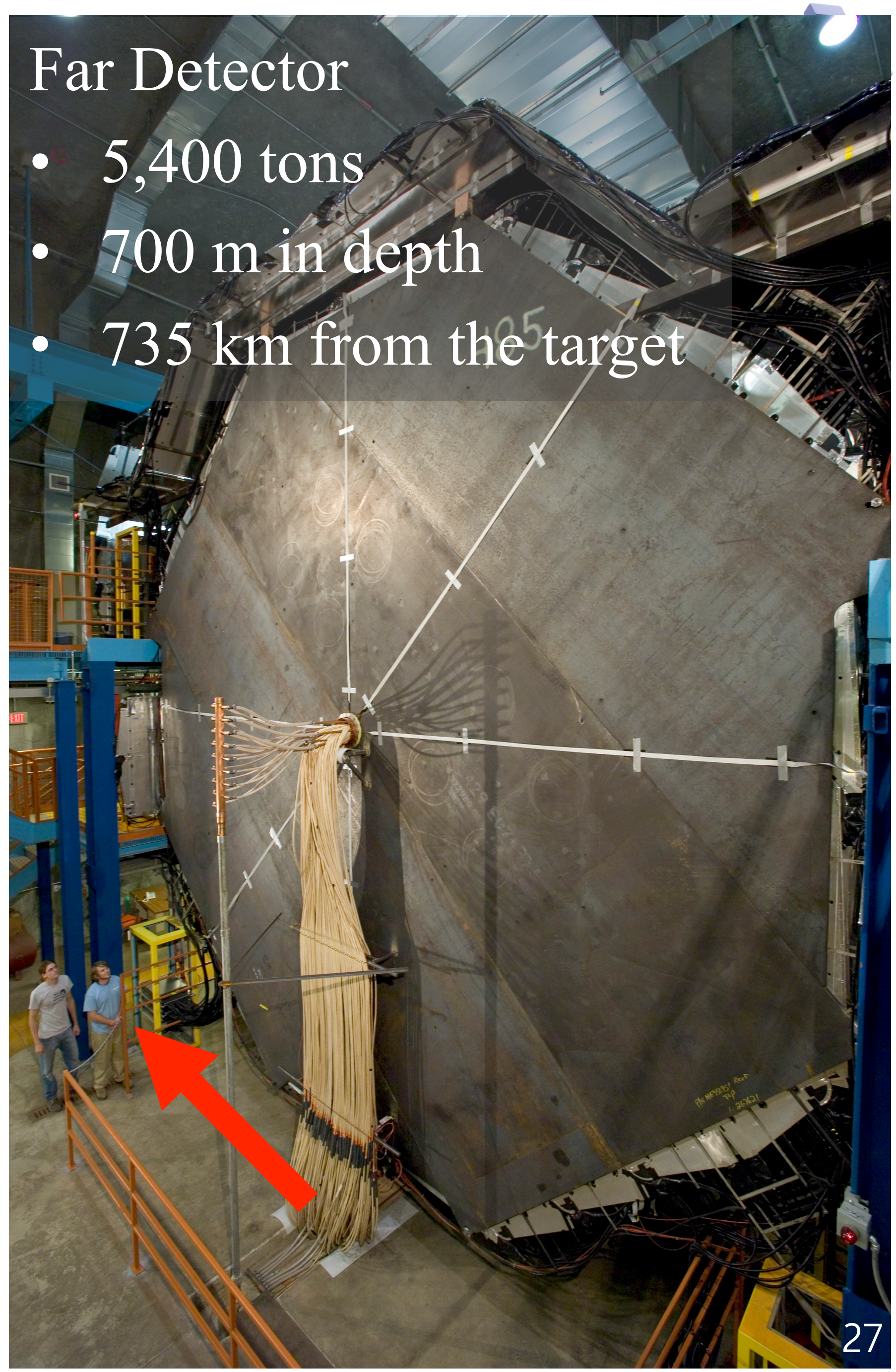
1.3 T toroidal magnetic field can distinguish neutrinos and antineutrinos



Strips in alternating directions allow 3D event reconstruction

MINOS Detectors

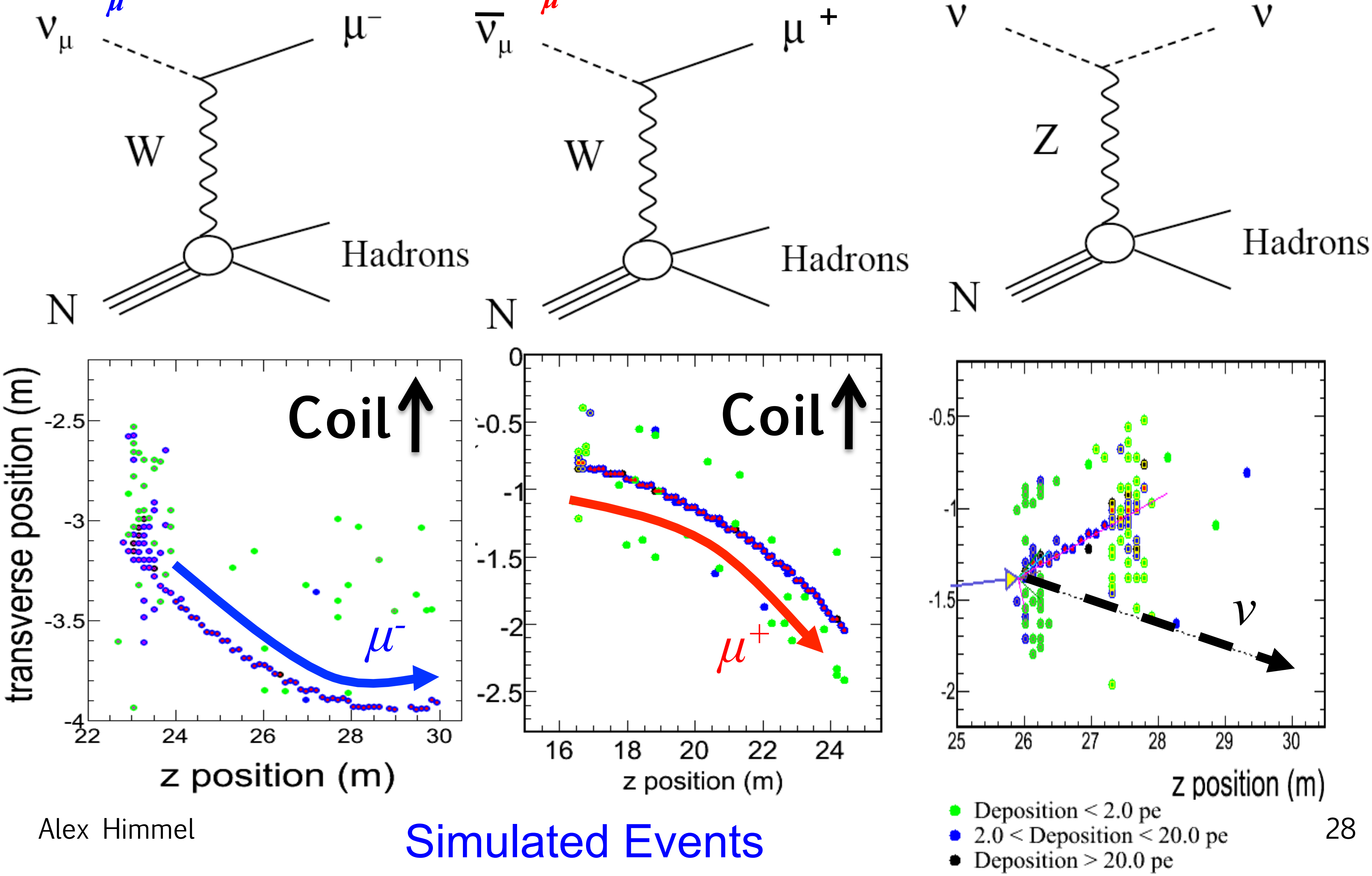
Near Detector
- 980 tons
- 100 m depth
- 1 km from the target



Far Detector
- 5,400 tons
- 700 m in depth
- 735 km from the target

MINOS Event Topologies

ν_μ CC Event | $\bar{\nu}_\mu$ CC Event | NC Event



Simulated Events

The Analyses

Neutrinos and Antineutrinos

Oscillation Analysis in Brief

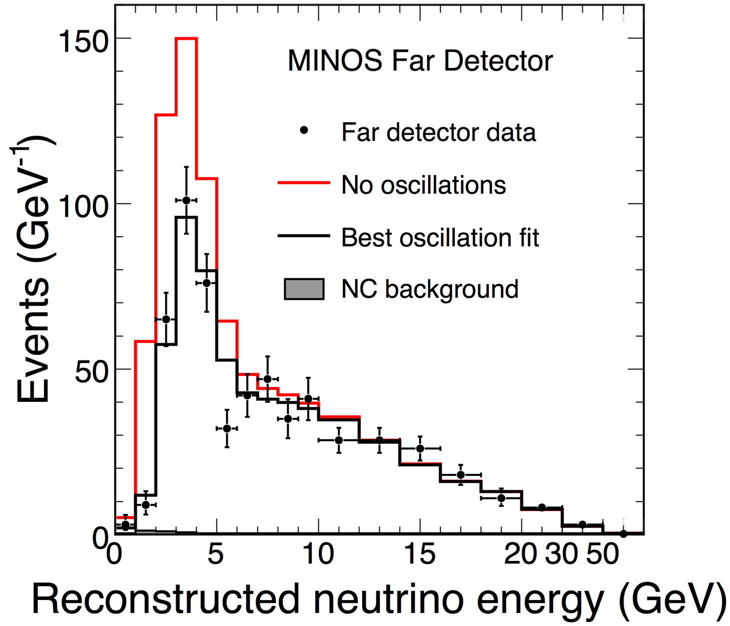
- Select (anti)neutrino events in the detectors
- Measure their energies to produce Near and Far detector spectra
- Use the Near Detector spectrum to predict the Far Detector spectrum independent of oscillations
- Fit the Far Detector data to measure oscillations

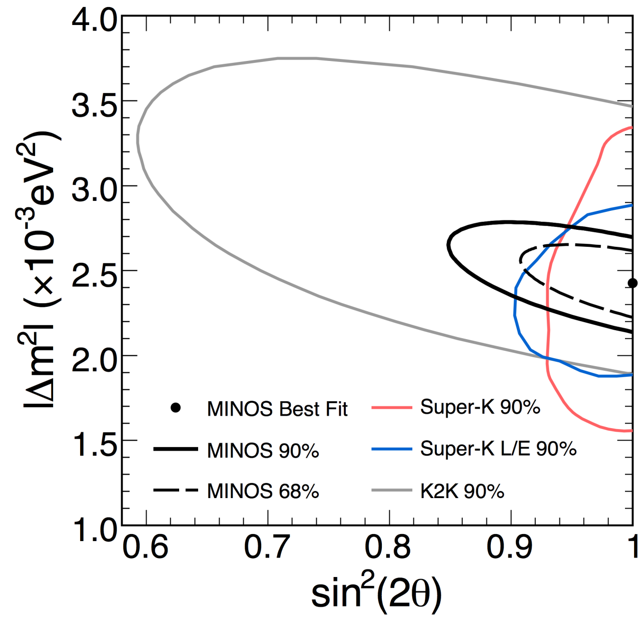
The Neutrino Analysis

Since our previous measurement…

- P. Adamson, et. al, Phys. Rev. Lett. 101:131802 (2008)

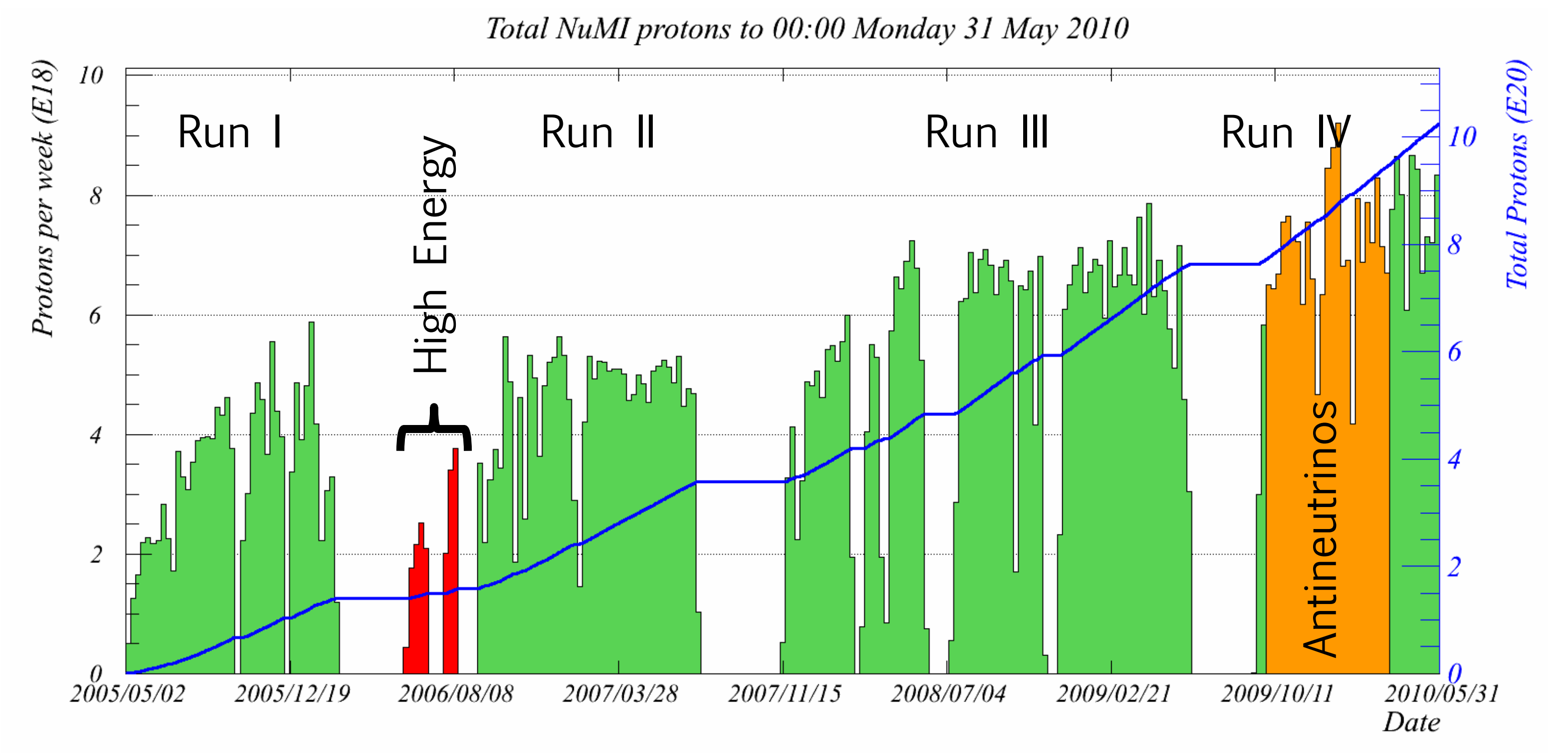
- Additional data
  - 3.4×10^{20} to 7.2×10^{20} protons-on-target
- Improvements in the analysis
  - Updated simulation and reconstruction
  - New selection improves low-energy efficiency
  - New shower energy estimator with 30% better low-energy resolution
  - Split the data set into bins of resolution
  - No charge sign cut – reclaim mis-identified neutrino events at low energy





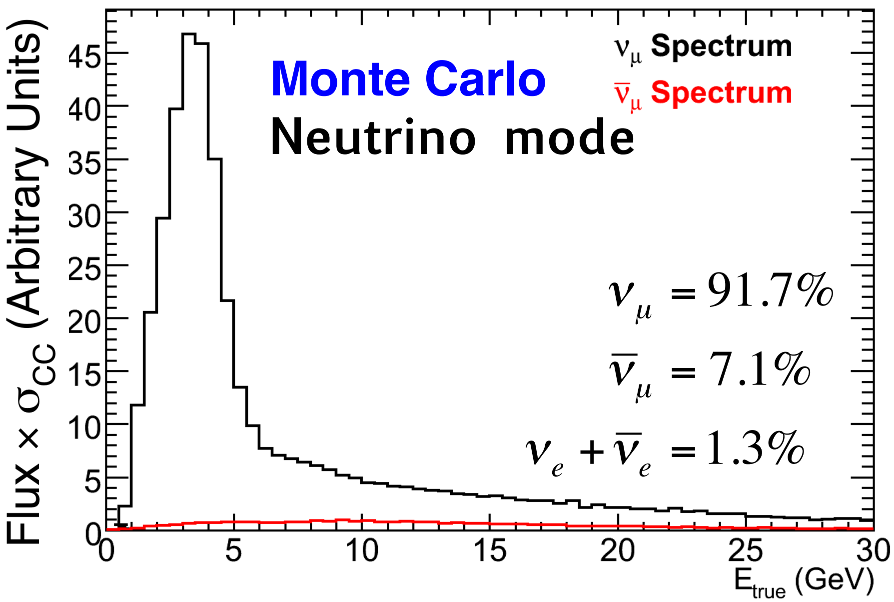
The Antineutrino Analysis

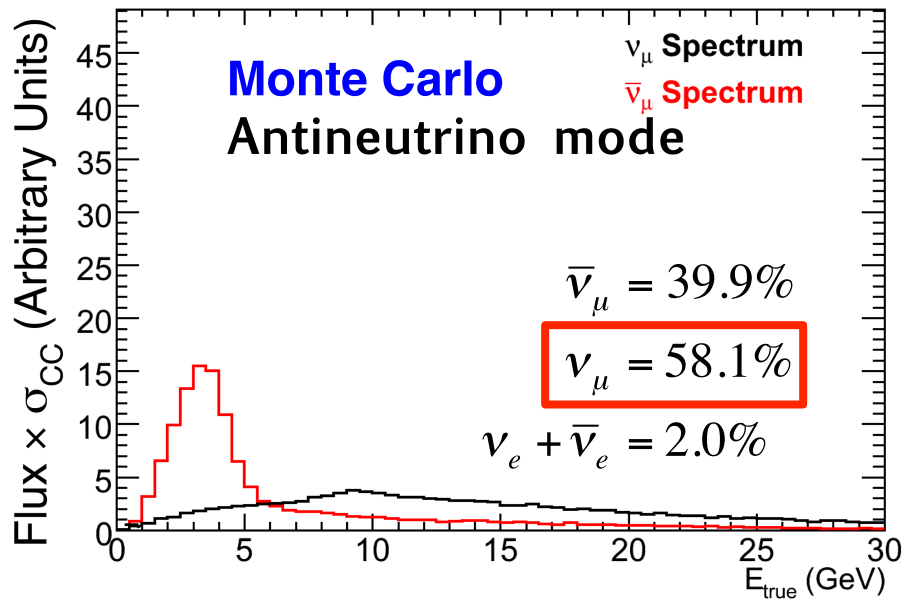
- Essentially the neutrino analysis of 2008
  - No resolution binning, shower estimator, new selector
  - Only stopped taking antineutrino data on March 22nd
- What's different with antineutrinos?
  - Lower statistics ~1/12th events
  - Larger wrong-sign component
  - Interactions are less hadronic



The Antineutrino Analysis

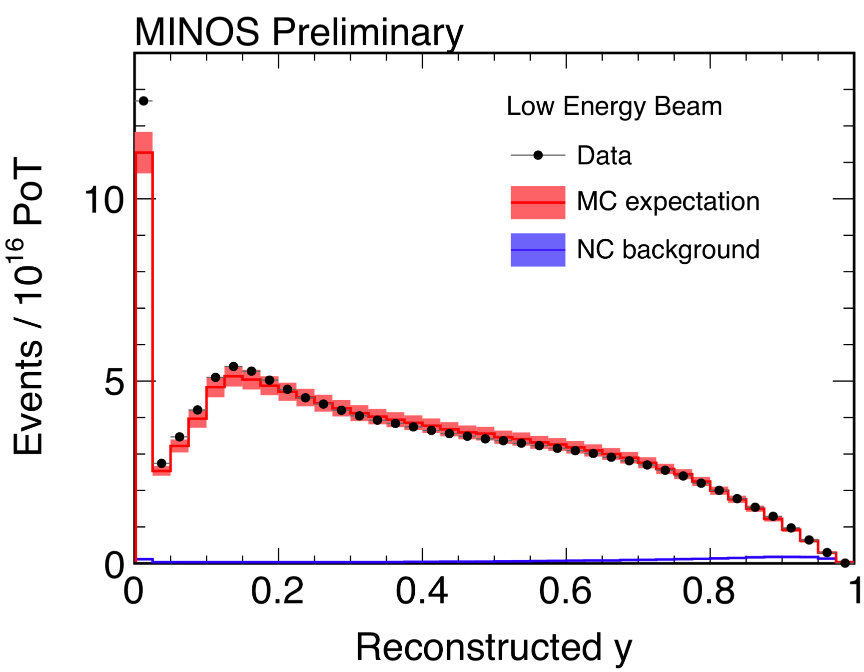
- Essentially the neutrino analysis of 2008
  - No resolution binning, shower estimator, new selector
  - Only stopped taking antineutrino data on March 22nd
- What's different with antineutrinos?
  - Lower statistics ~1/12th events
  - Larger wrong-sign component
  - Interactions are less hadronic



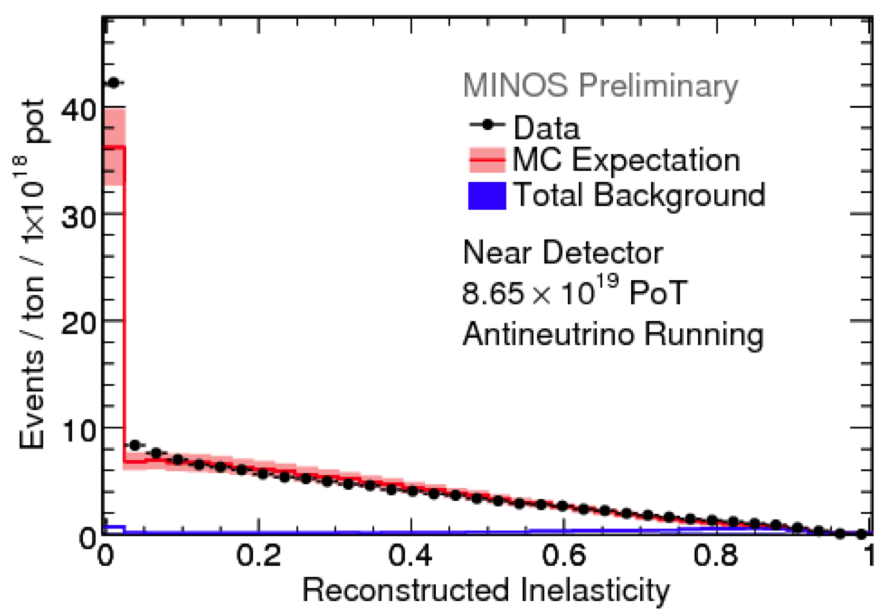


The Antineutrino Analysis

- Essentially the neutrino analysis of 2008
  - No resolution binning, shower estimator, new selector
  - Only stopped taking antineutrino data on March 22nd
- What's different with antineutrinos?
  - Lower statistics ~1/12th events
  - Larger wrong-sign component
  - Interactions are less hadronic



Neutrinos



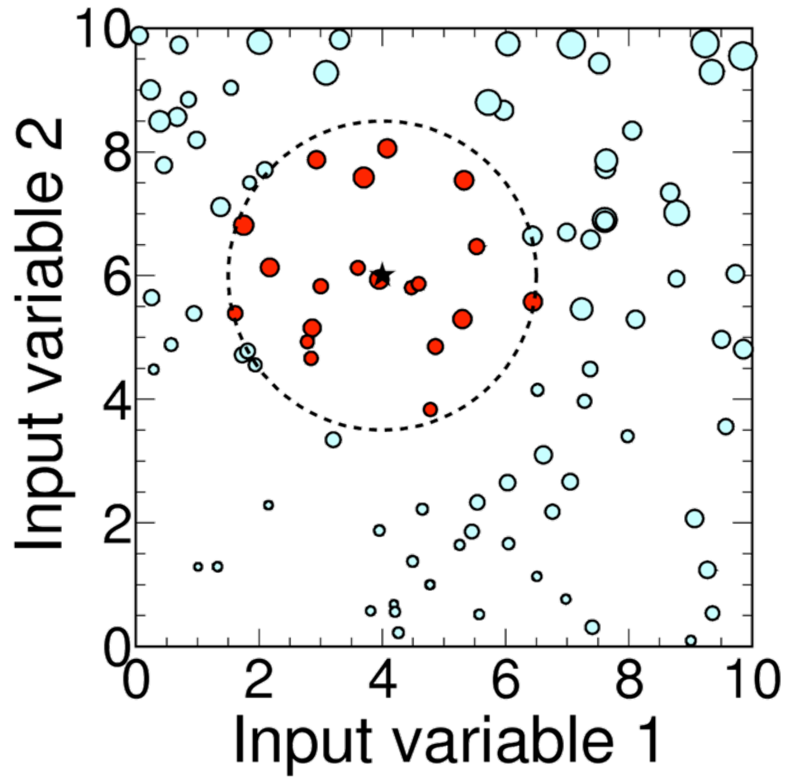
Antineutrinos

Oscillation Analysis in Brief

- Select (anti)neutrino events in the detectors
- Measure their energies to produce Near and Far detector spectra
- Use the Near Detector spectrum to predict the Far Detector spectrum independent of oscillations
- Fit the Far Detector data to measure oscillations

Common Selection

- Basic selection
  - In-time with the spill
  - In the fiducial volume
  - At least 1 reconstructed track
- CC/NC separation using a kNN algorithm
  - Compare to monte carlo events
- 4-parameter comparison
  - Track length
  - Mean energy of track hits
  - Energy fluctuations along the track
  - Transverse track profile

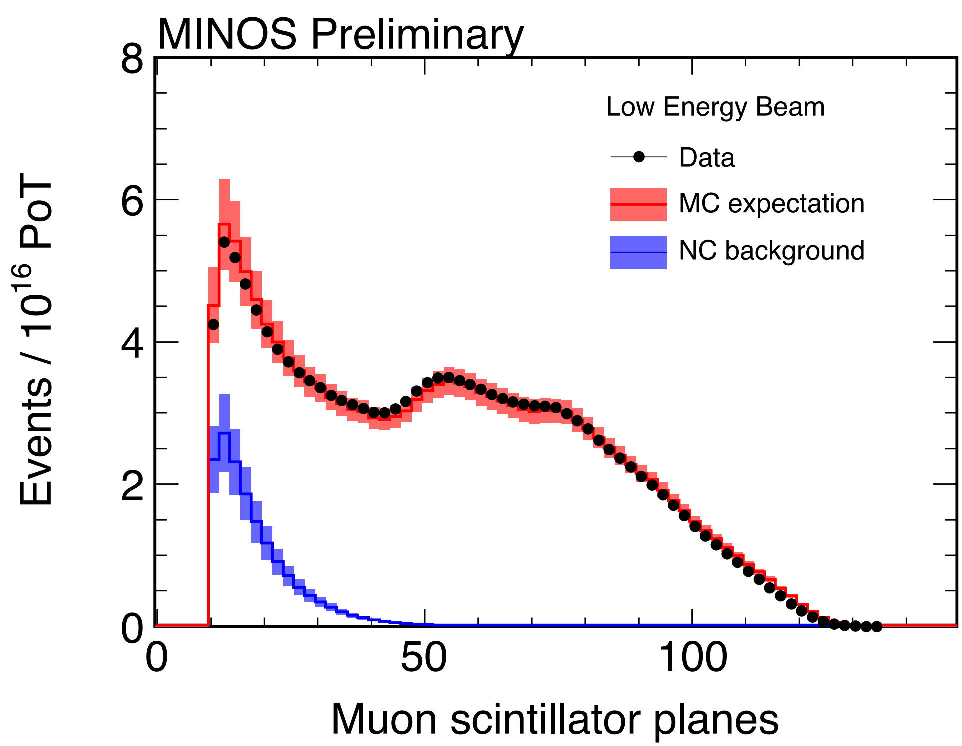


k-Nearest Neighbors

“kNN”

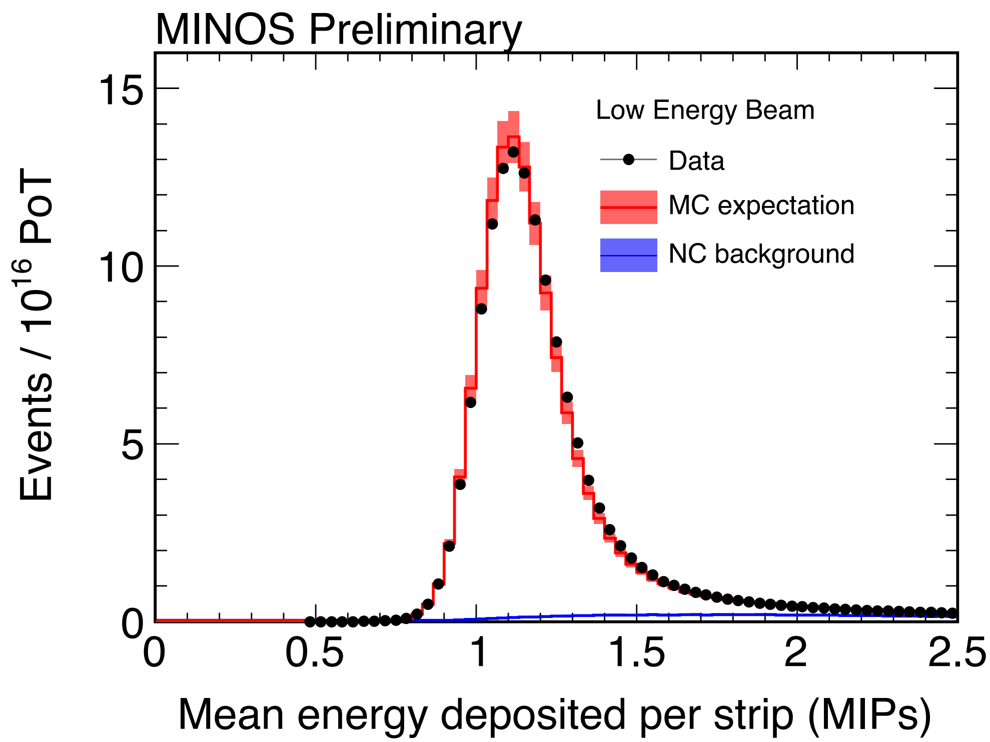
Common Selection

- Basic selection
  - In-time with the spill
  - In the fiducial volume
  - At least 1 reconstructed track
- CC/NC separation using a kNN algorithm
  - Compare to monte carlo events
- 4-parameter comparison
  - Track length
  - Mean energy of track hits
  - Energy fluctuations along the track
  - Transverse track profile



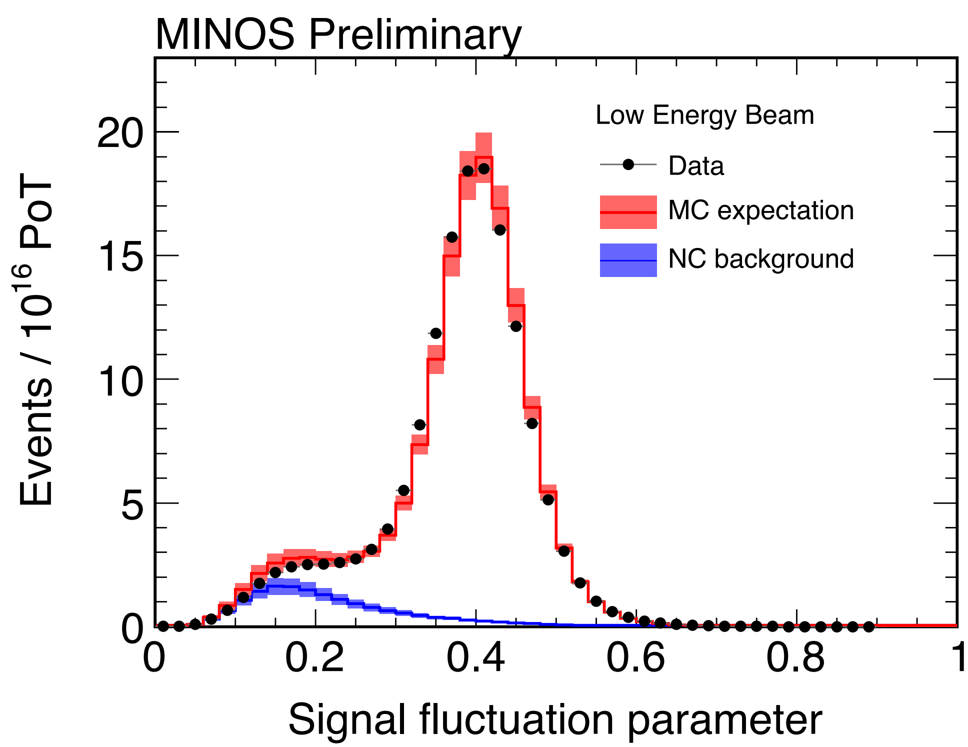
Common Selection

- Basic selection
  - In-time with the spill
  - In the fiducial volume
  - At least 1 reconstructed track
- CC/NC separation using a kNN algorithm
  - Compare to monte carlo events
- 4-parameter comparison
  - Track length
  - Mean energy of track hits
  - Energy fluctuations along the track
  - Transverse track profile



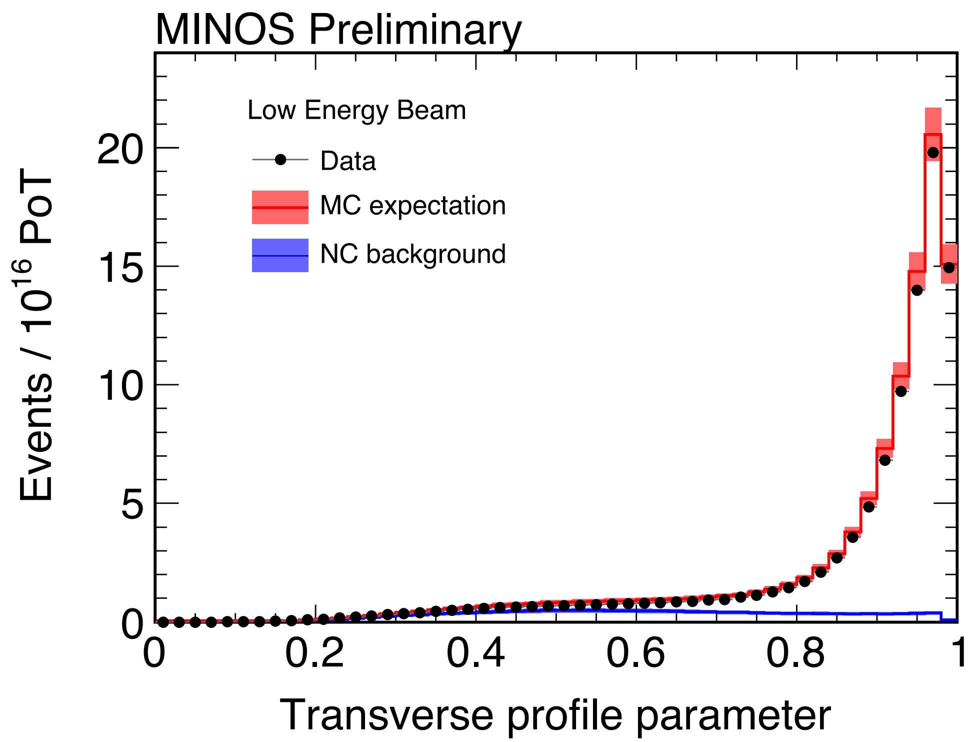
Common Selection

- Basic selection
  - In-time with the spill
  - In the fiducial volume
  - At least 1 reconstructed track
- CC/NC separation using a kNN algorithm
  - Compare to monte carlo events
- 4-parameter comparison
  - Track length
  - Mean energy of track hits
  - Energy fluctuations along the track
  - Transverse track profile



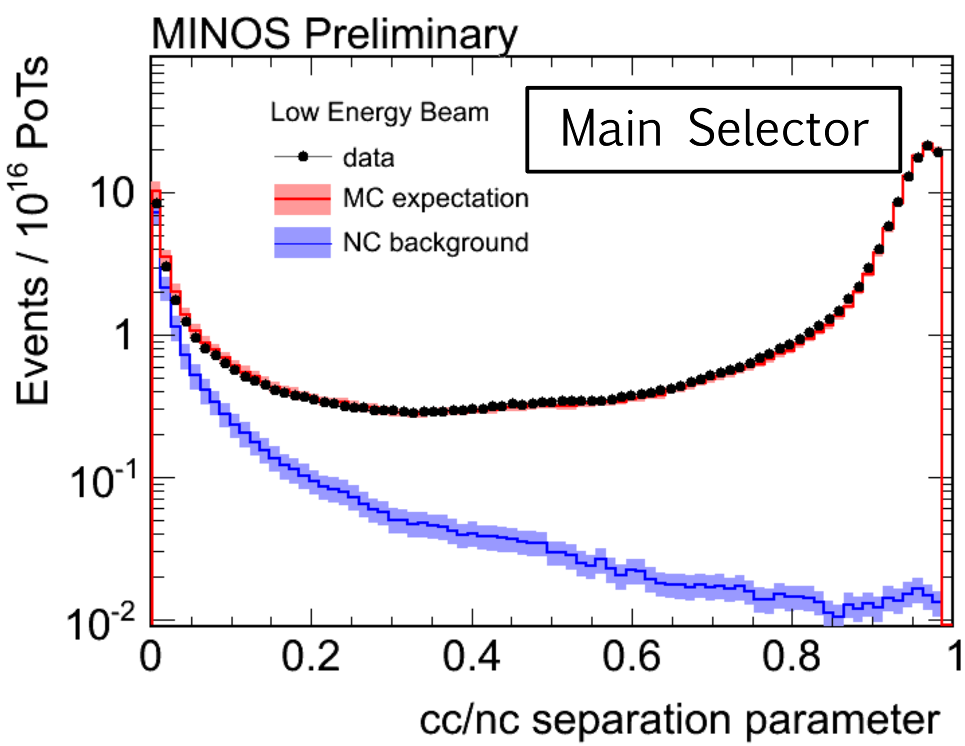
Common Selection

- Basic selection
  - In-time with the spill
  - In the fiducial volume
  - At least 1 reconstructed track
- CC/NC separation using a kNN algorithm
  - Compare to monte carlo events
- 4-parameter comparison
  - Track length
  - Mean energy of track hits
  - Energy fluctuations along the track
  - Transverse track profile

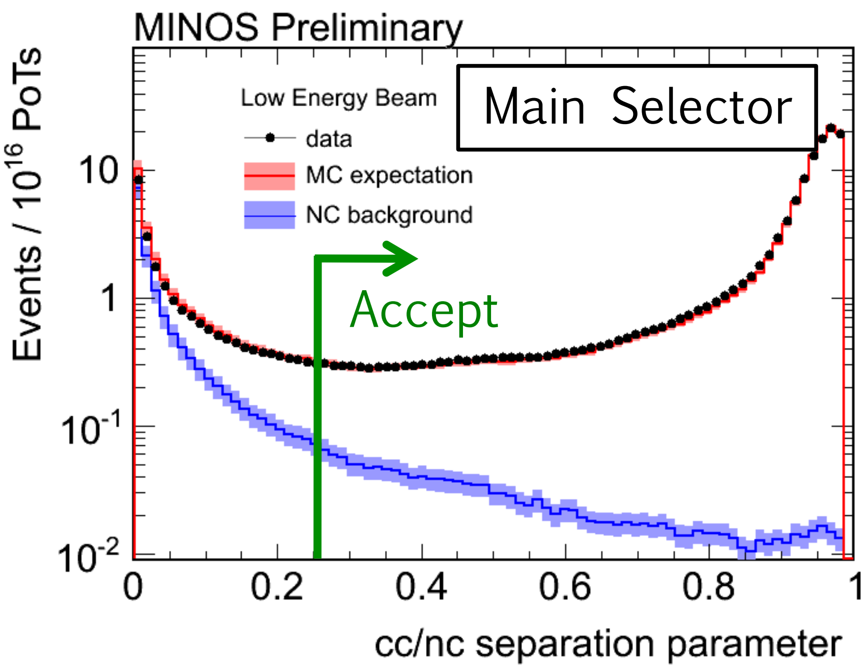


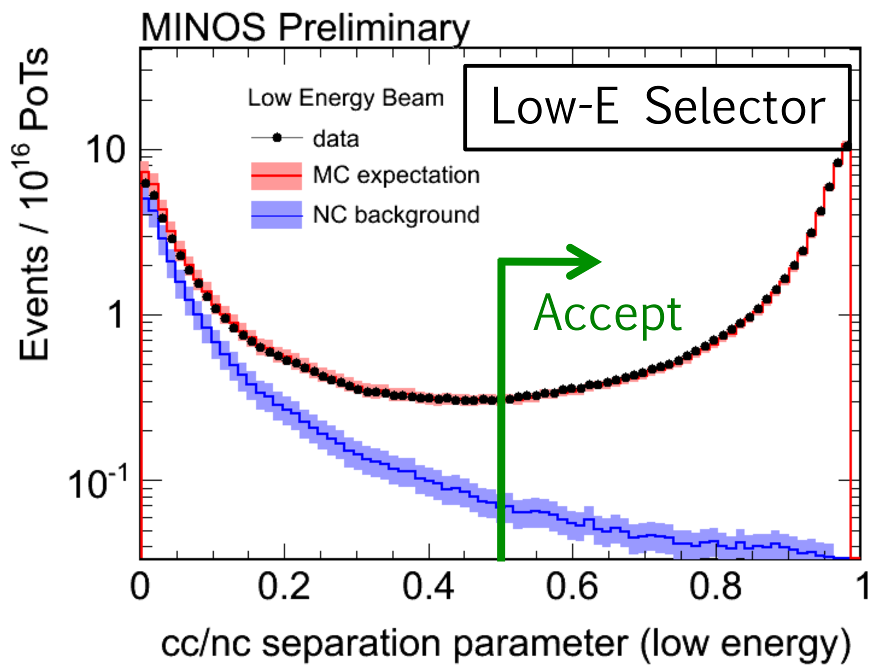
Common Selection

- Basic selection
  - In-time with the spill
  - In the fiducial volume
  - At least 1 reconstructed track
- CC/NC separation using a kNN algorithm
  - Compare to monte carlo events
- 4-parameter comparison
  - Track length
  - Mean energy of track hits
  - Energy fluctuations along the track
  - Transverse track profile



Neutrino Selection

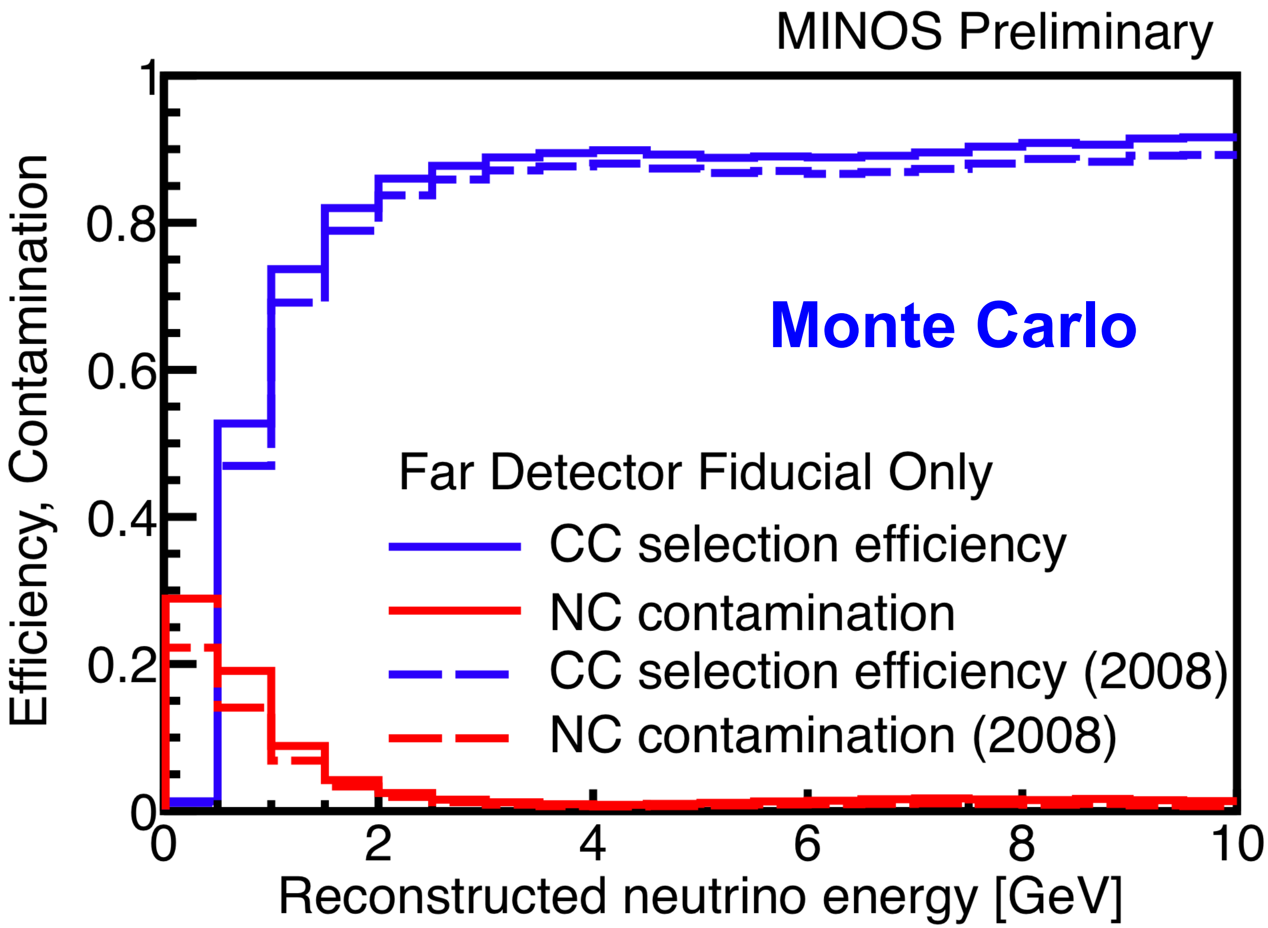




- Added a second selector that accepts lower energy tracks
  - Number of planes in the track
  - Energy deposition at the end of the track
  - Amount of scattering

- The final selection is a logical OR of these two cuts.

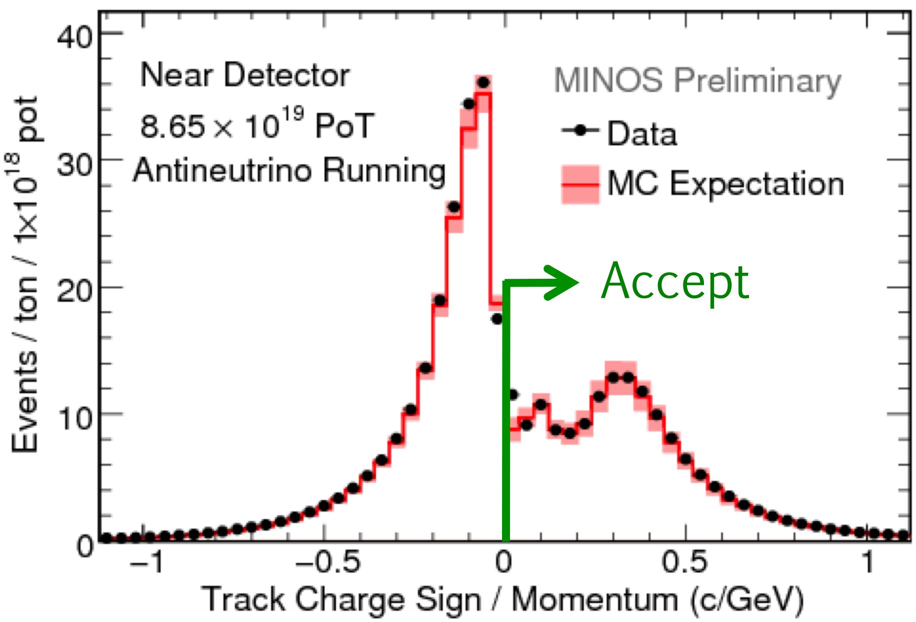
Neutrino Selection

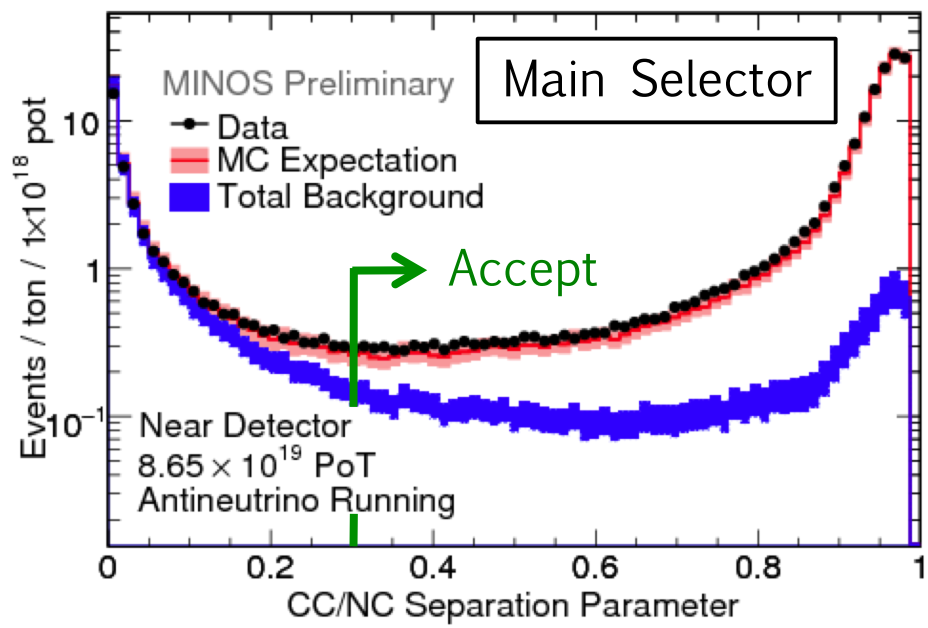


- Increase sensitivity by improving efficiency (89% vs. 87%) at the expense of contamination (1.7% vs. 1.2%)

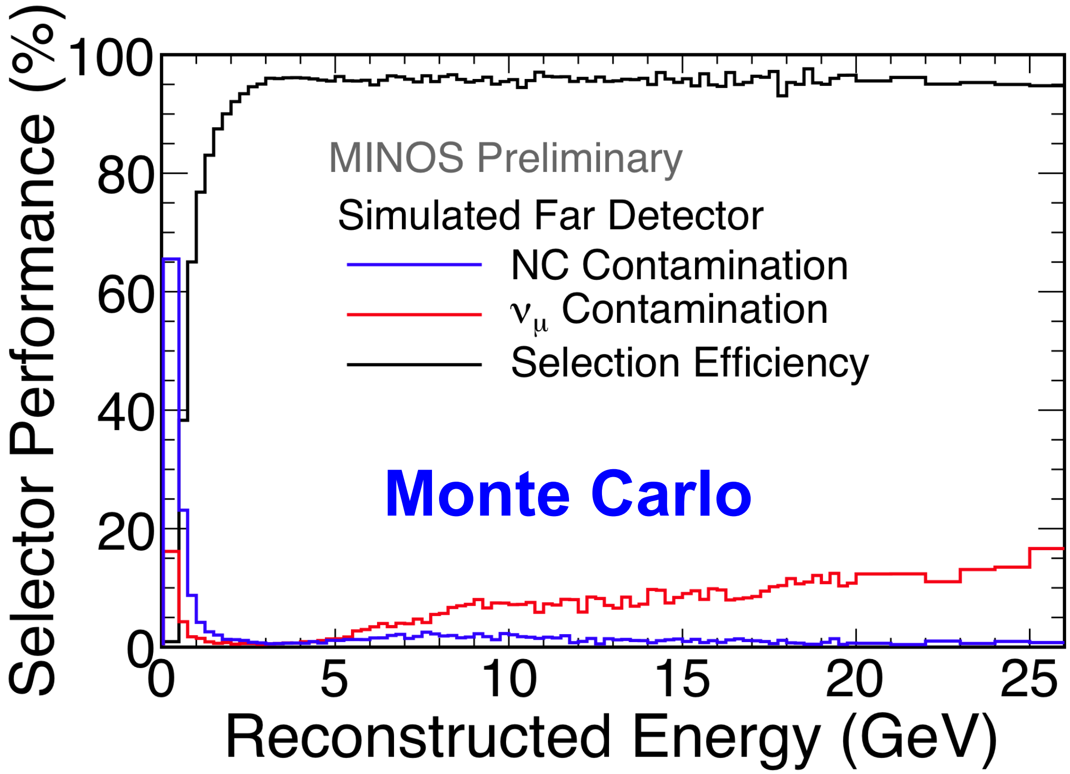
Antineutrino Selection

- Accept only events with positive reconstructed charge
- Use the Main CC/NC Selector from the neutrino analysis
  - Removes NC and high-y CC interactions
- Data/MC agreement comparable to that seen for neutrinos.





Antineutrino Efficiency & Purity



	Signal	Bkgd.
0-6 GeV	106	1.9
6-20 GeV	38	4.3
> 20 GeV	8	3.0

High energy ν_μ contamination does not affect the oscillation result

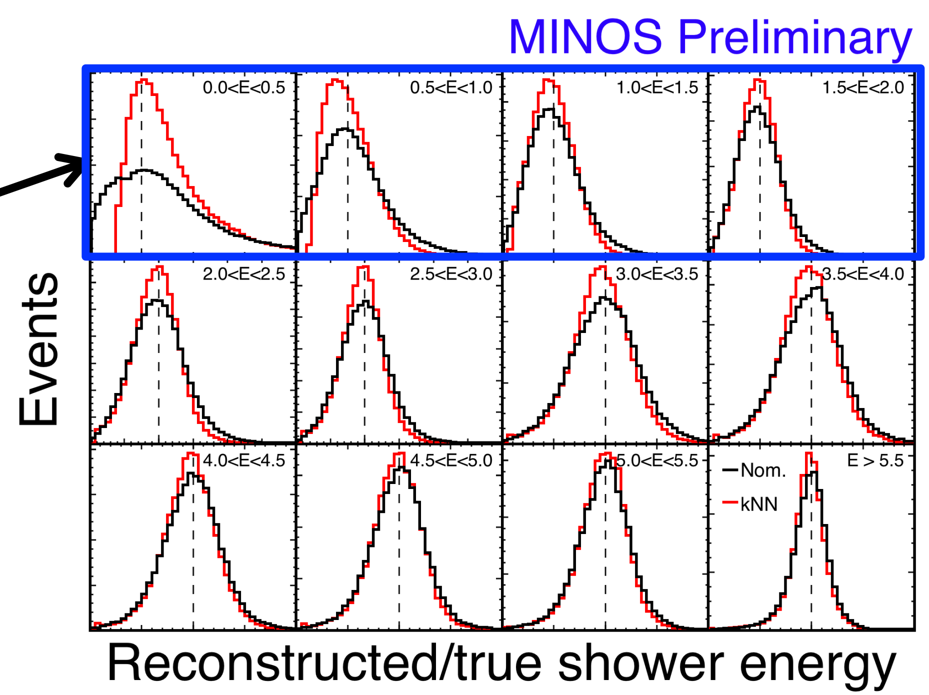
Oscillation Analysis in Brief

- Select (anti)neutrino events in the detectors
- Measure their energies to produce Near and Far detector spectra
- Use the Near Detector spectrum to predict the Far Detector spectrum independent of oscillations
- Fit the Far Detector data to measure oscillations

New Shower Energy Estimator

- Construct a three-parameter kNN using:
  - the shower energy within 1 m of the track vertex
  - the number of planes in the shower
  - the energy in the second reconstructed shower
- Estimator is the mean energy of the nearest neighbors

~30% better resolution below 2 GeV

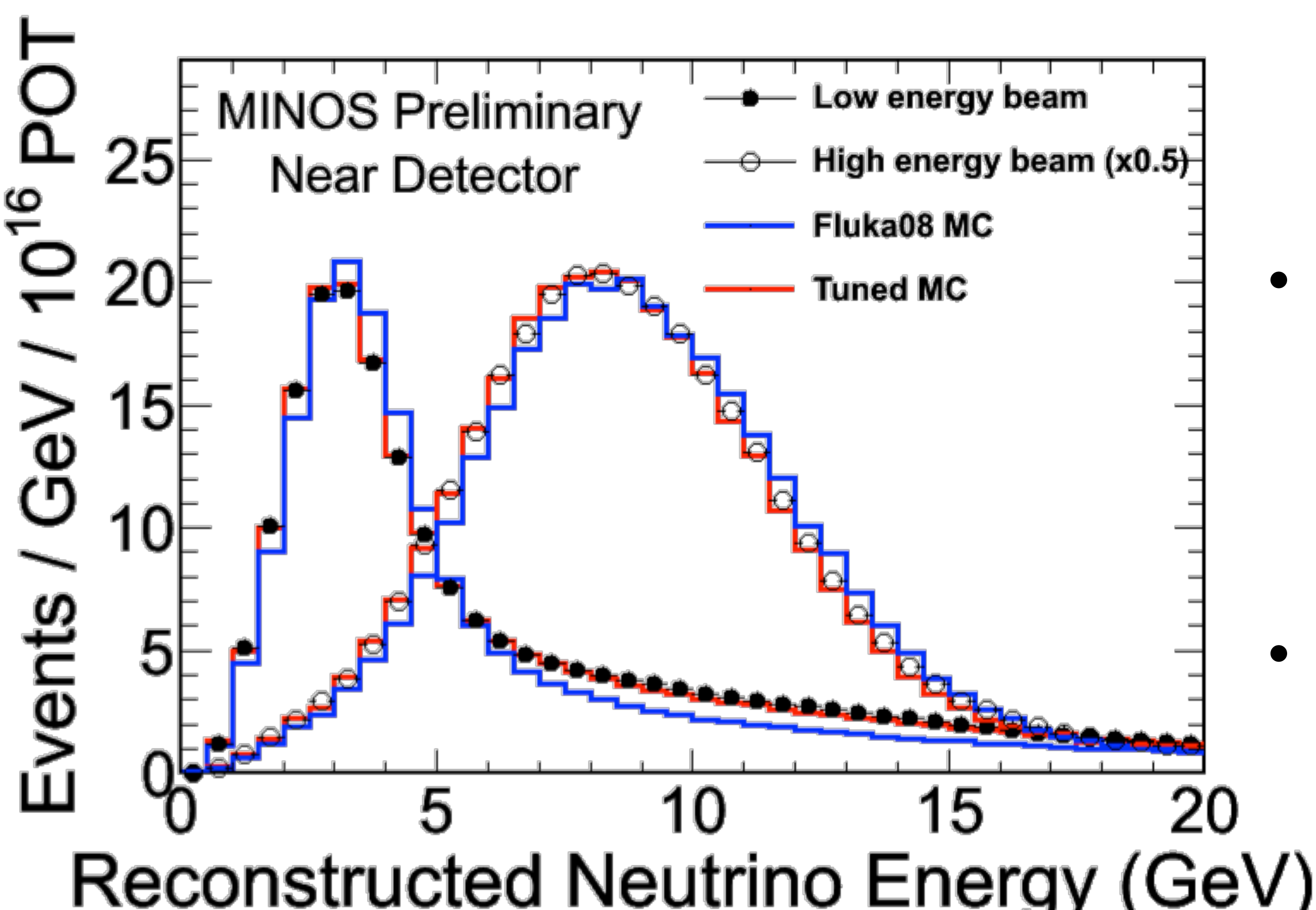


Monte Carlo

Original Energy

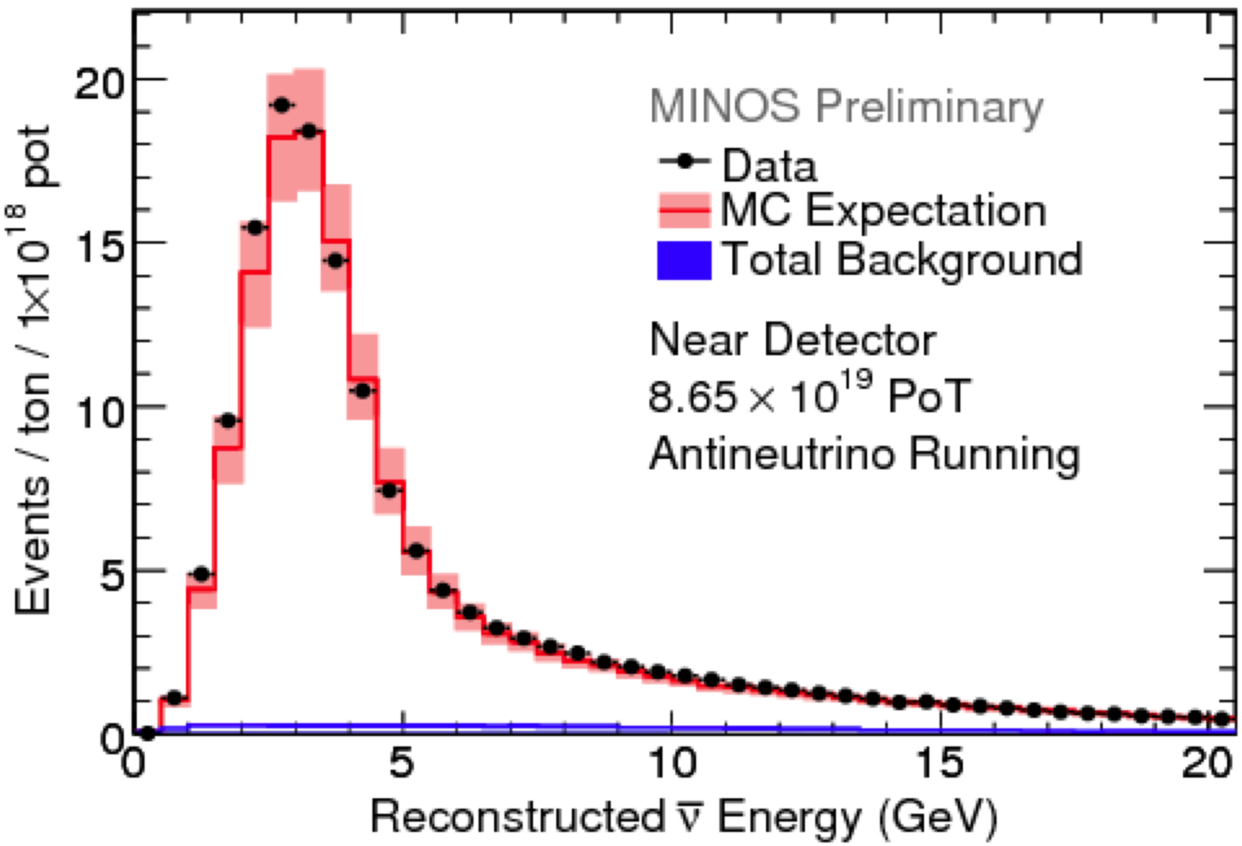
New Estimator

Neutrino Near Detector Data



- Majority of data taken in Low Energy Beam
- High Energy Beam gives us more events above the oscillation dip
- Other beam configurations used for systematics, commissioning, MC tuning

Antineutrino Near Detector Data

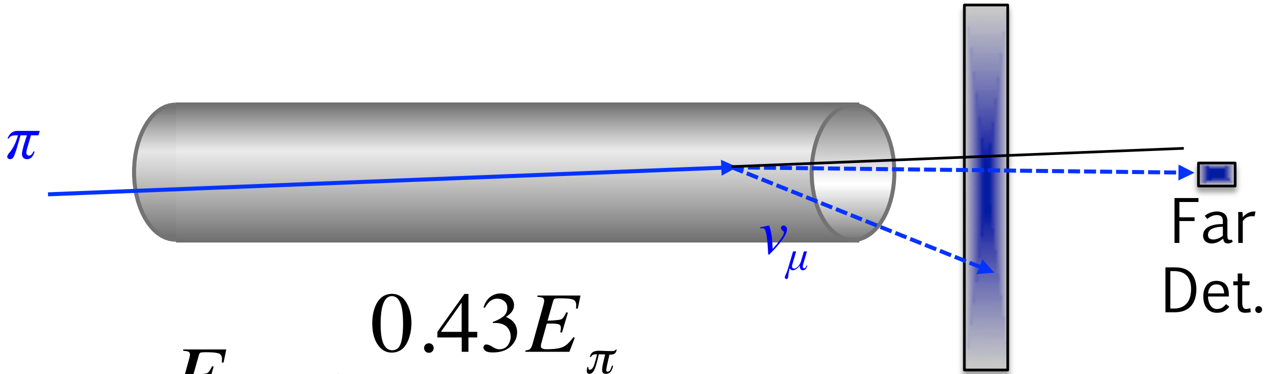


Flux and cross-section uncertainties cancel when extrapolated from Near to Far detector.

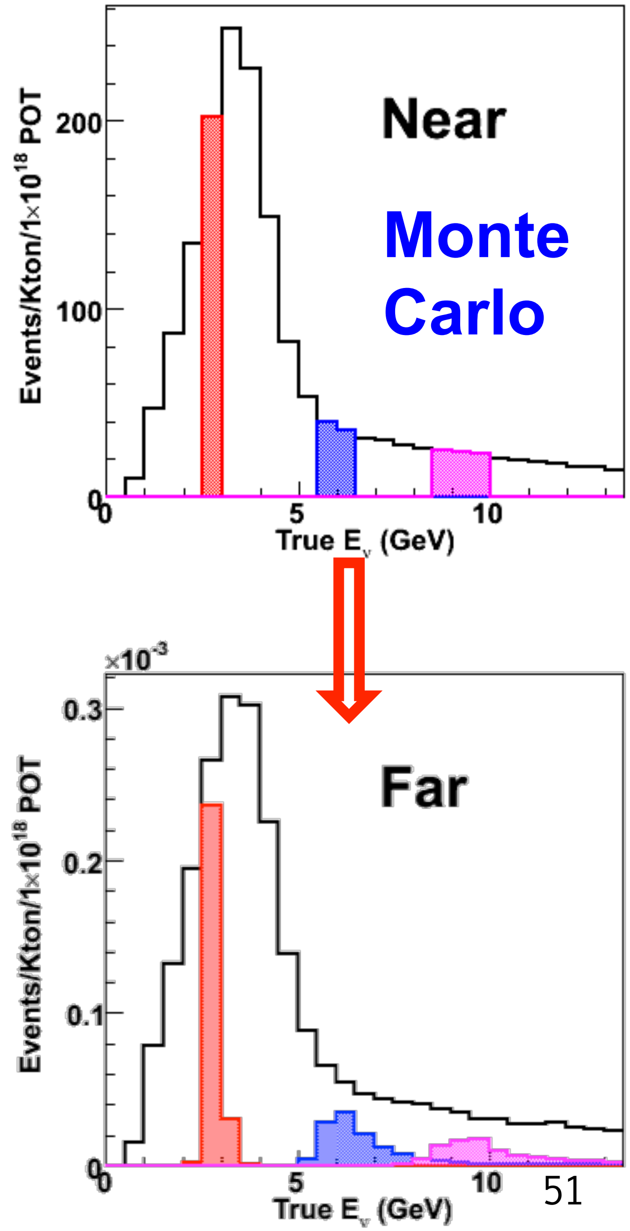
Oscillation Analysis in Brief

- Select (anti)neutrino events in the detectors
- Measure their energies to produce Near and Far detector spectra
- Use the Near Detector spectrum to predict the Far Detector spectrum independent of oscillations
- Fit the Far Detector data to measure oscillations

Near-to-Far Extrapolation



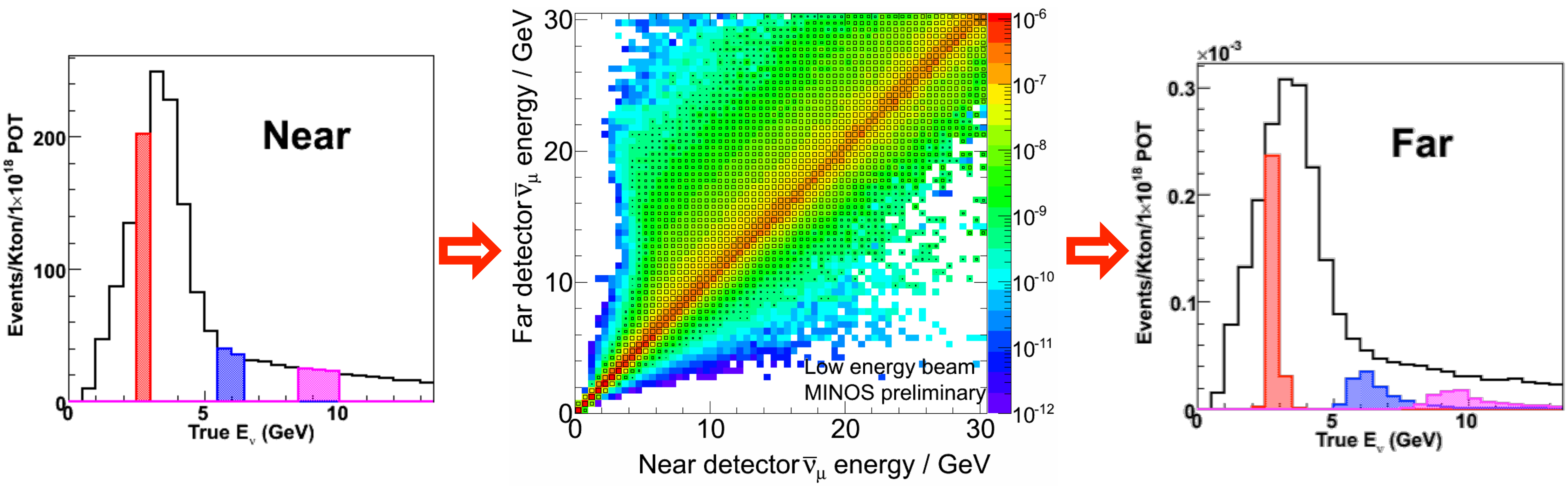
$$E_\nu \approx \frac{0.43 E_\pi}{1+\gamma_\pi^2 \theta_\nu^2}$$



- The Near Detector and Far Detector spectra are not identical.
  - Due to π/K decay kinematics, neutrino energy varies with angle.
  - The Near Detector covers a wider solid angle
  - Higher energy π travel further and decay closer to the Near Detector

Beam Matrix Extrapolation

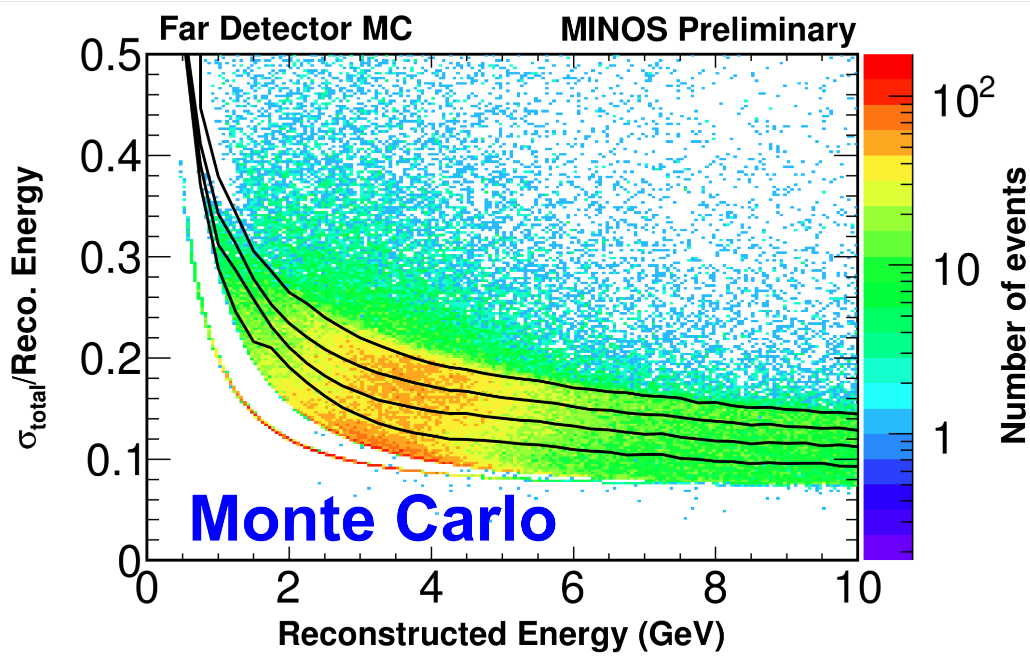
- A beam matrix transports measured Near spectrum to Far
- Matrix encapsulates knowledge of meson decay kinematics and beamline geometry
- MC used to correct for energy smearing and acceptance



Monte Carlo

Resolution Binning

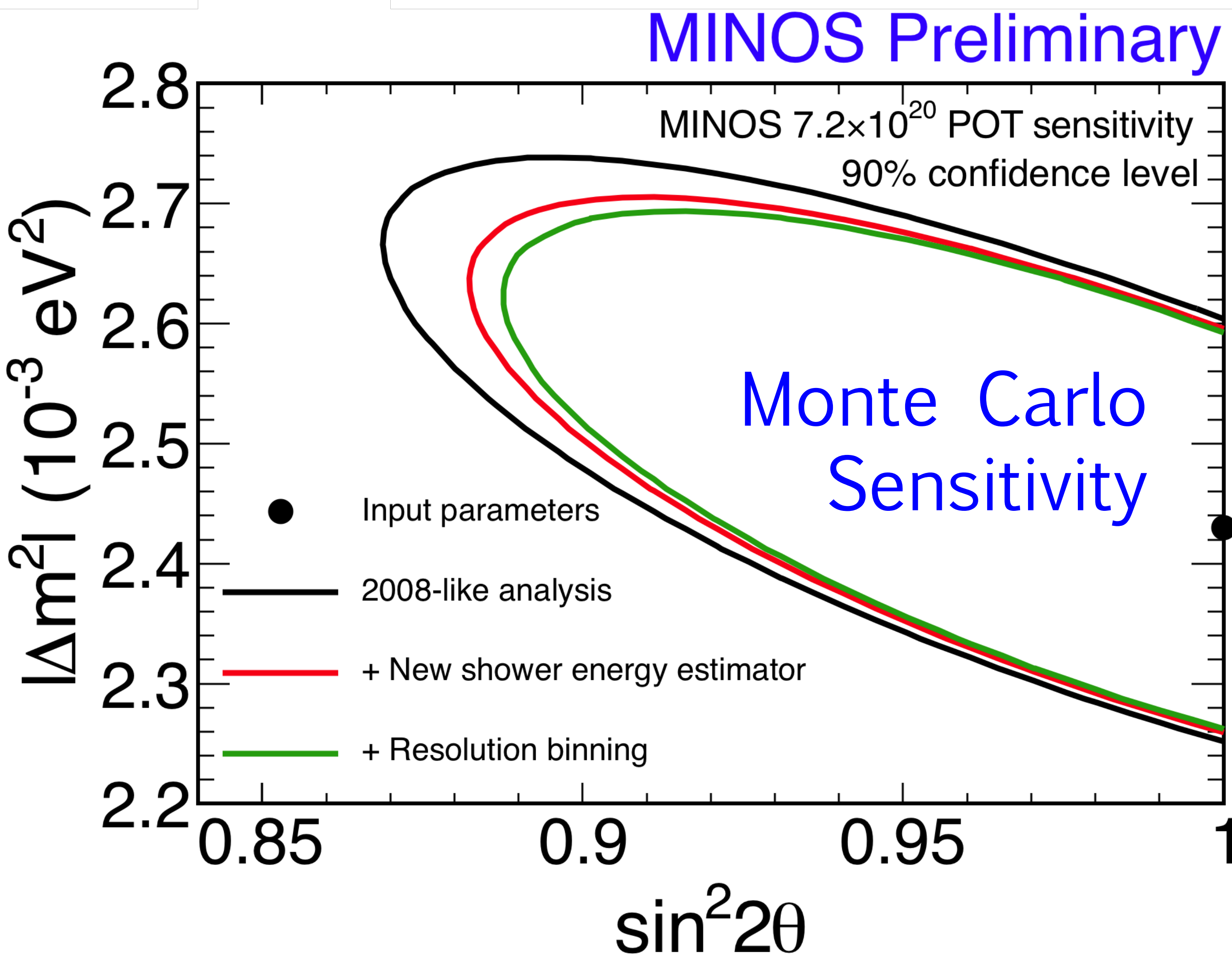
- Improve statistical power by separating high and low resolution events.
- MC parameterization of the energy resolution
- 6 Resolution bins
  - 5 bins for events with negative reconstructed curvature
  - 1 bin for events with positive reconstructed curvature (30% true ν_μ)



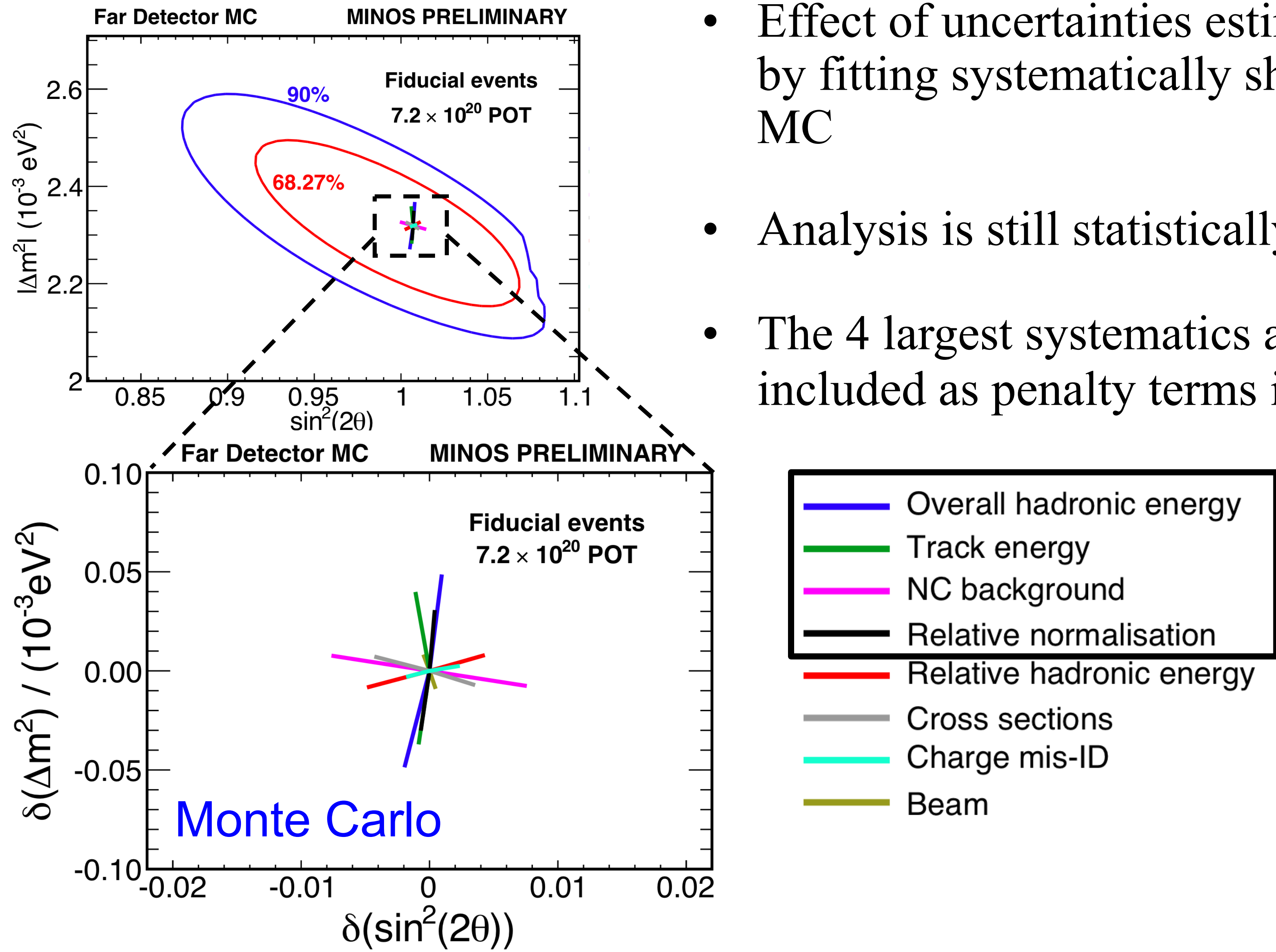
Oscillation Analysis in Brief

- Select (anti)neutrino events in the detectors
- Measure their energies to produce Near and Far detector spectra
- Use the Near Detector spectrum to predict the Far Detector spectrum independent of oscillations
- Fit the Far Detector data to measure oscillations

Analysis Improvements

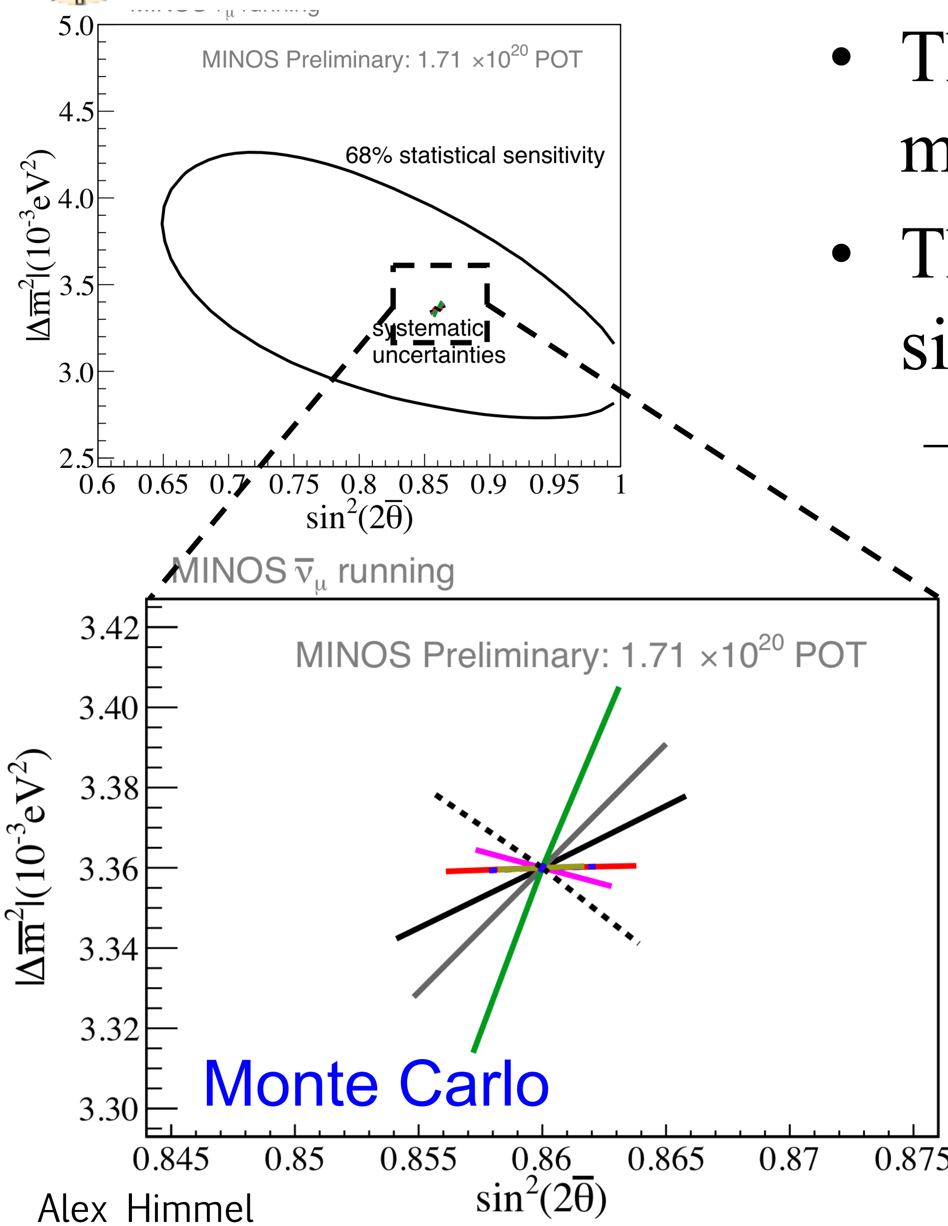


Neutrino Systematics

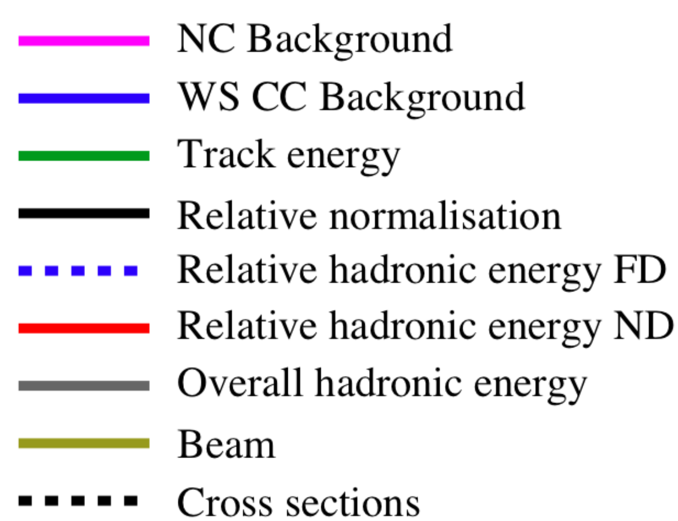


- Effect of uncertainties estimated by fitting systematically shifted MC
- Analysis is still statistically limited
- The 4 largest systematics are included as penalty terms in the fit.

Antineutrino Systematics



- The antineutrino analysis is even more statistically limited.
- The two analyses have very similar systematics
  - Though sizes of the effects are not the same.



The Results

Blind Analysis

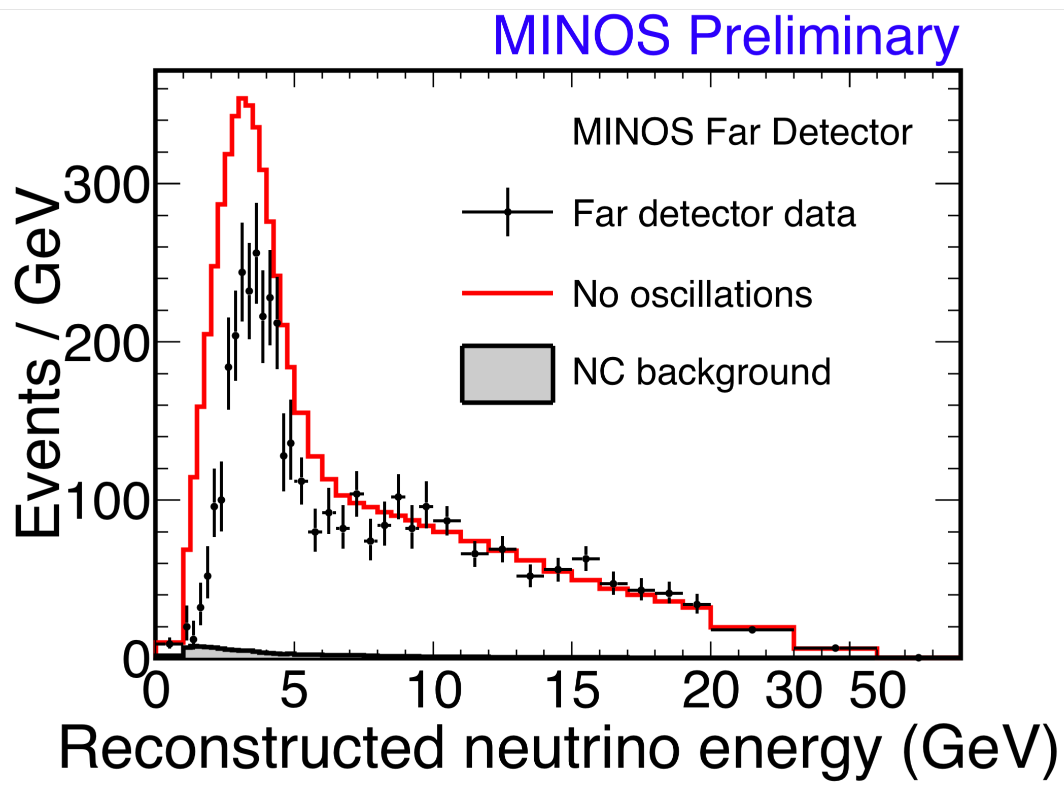
- These results are obtained from blind analyses
  - Finalized before looking at the full Far Detector data
    - selection cuts
    - data samples
    - extrapolation techniques
    - fitting routines
    - systematic uncertainties
- No changes have been made after box opening

And so…on to the results!

Far Detector Neutrino Data

➔**2,451** expected without oscillations

➔**1,986** observed events

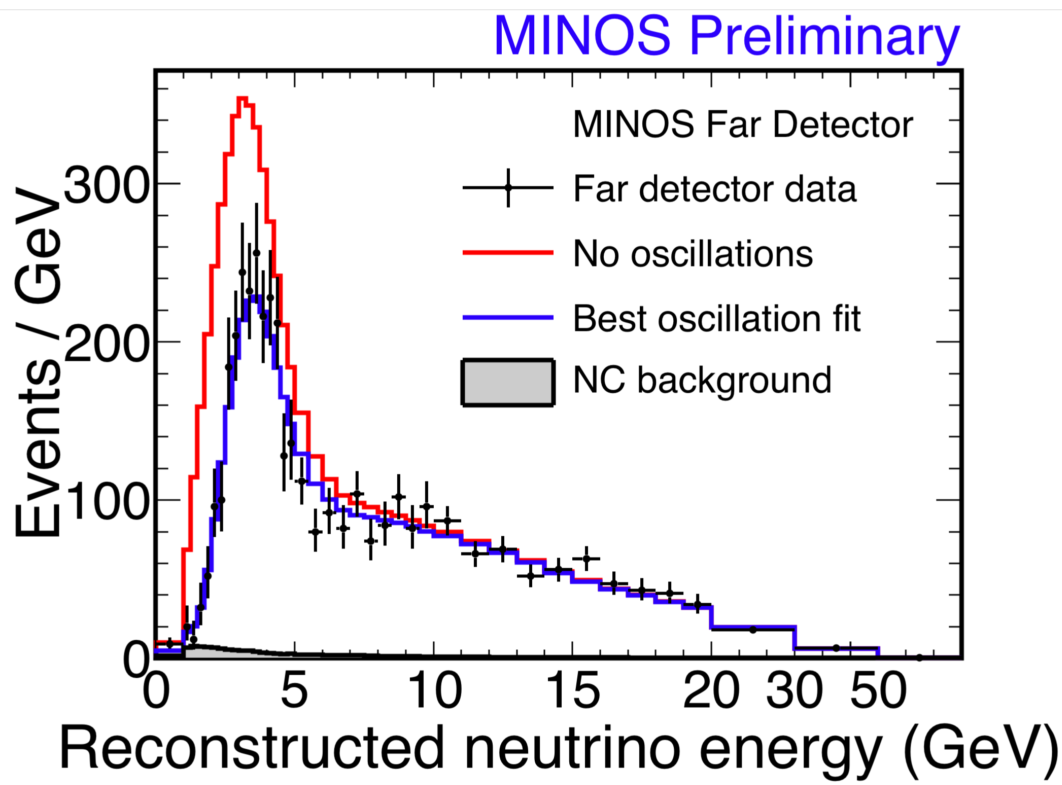


Far Detector Neutrino Data

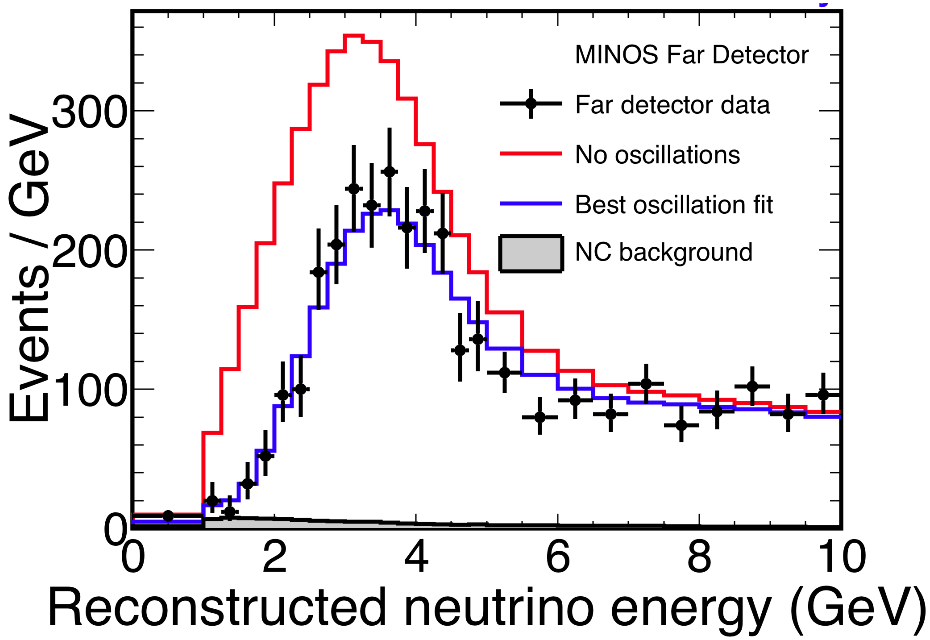
➔**2,451** expected without oscillations

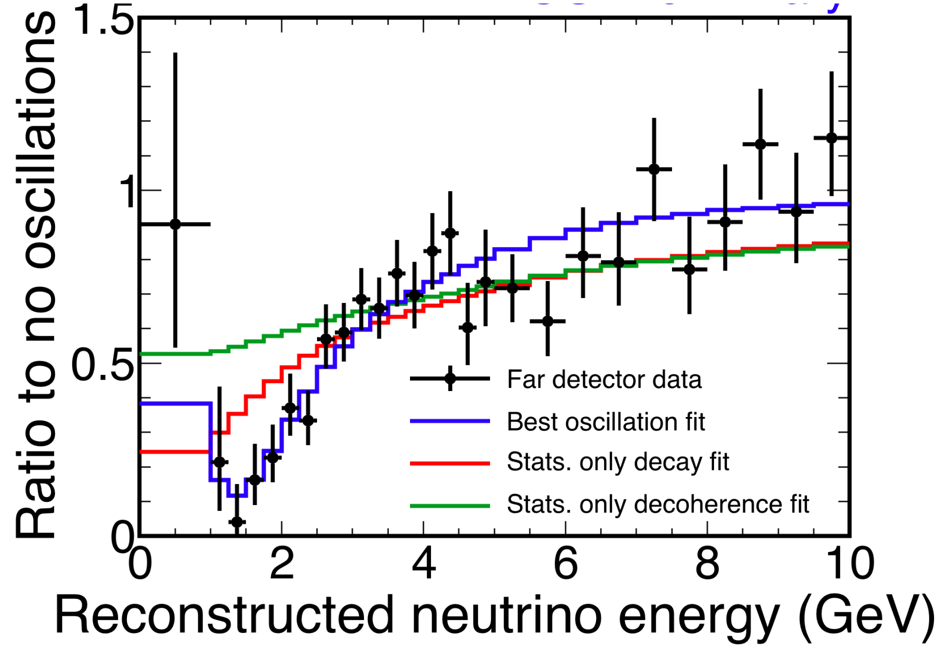
➔**1,986** observed events

Oscillations fit the data well – 66% of fake experiments have a worse χ^2



Far Detector Neutrino Data

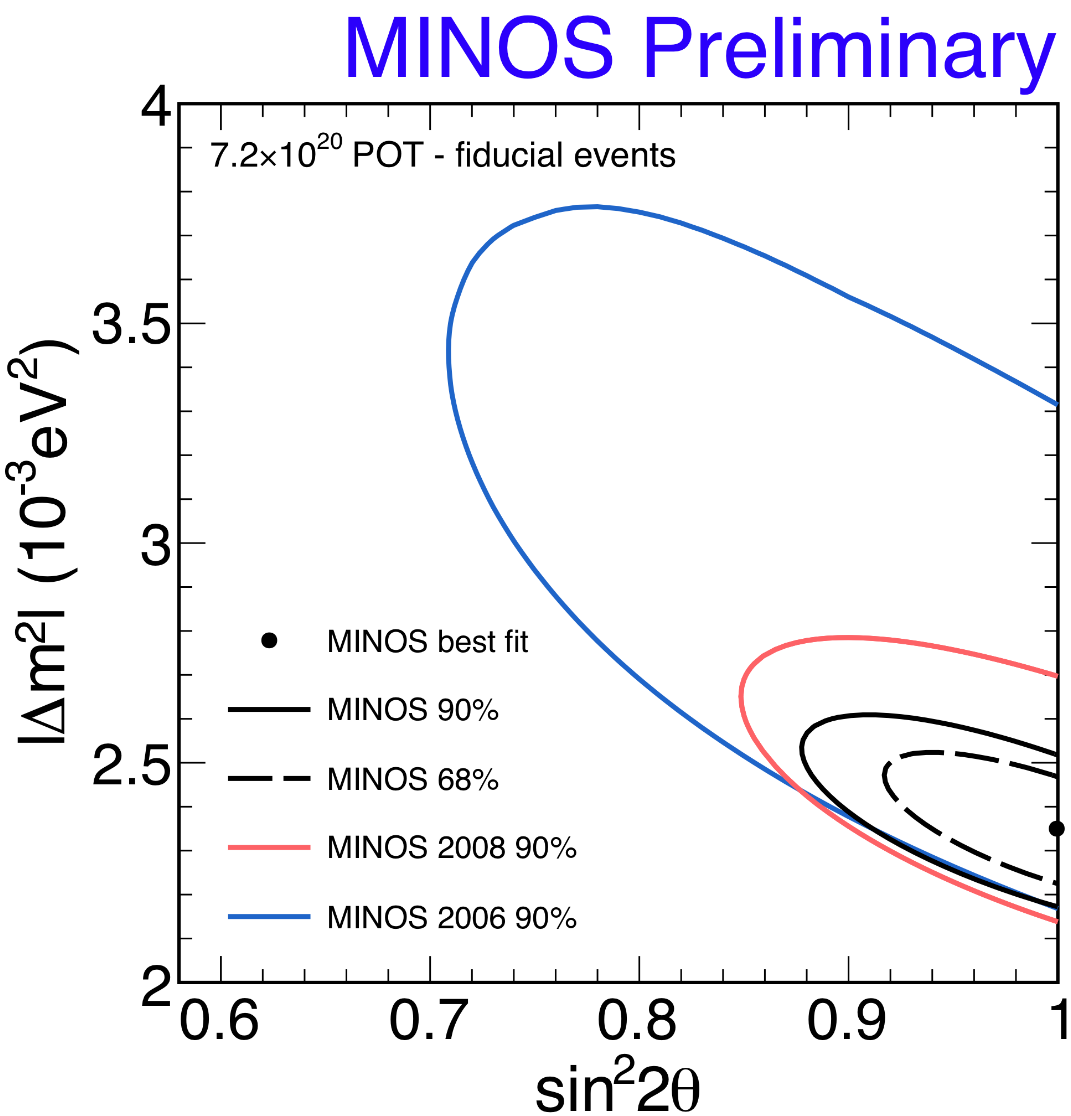




- Can see the characteristic dip of oscillations.
- Disfavor in a statistics-only fit:
  - Pure decay† at > **6σ**
  - Pure decoherence‡ at > **8σ**

†G.L. Fogli *et al.*, PRD 67:093006 (2003)
‡V. Barger *et al.*,PRL 82:2640 (1999)

Neutrino Contour

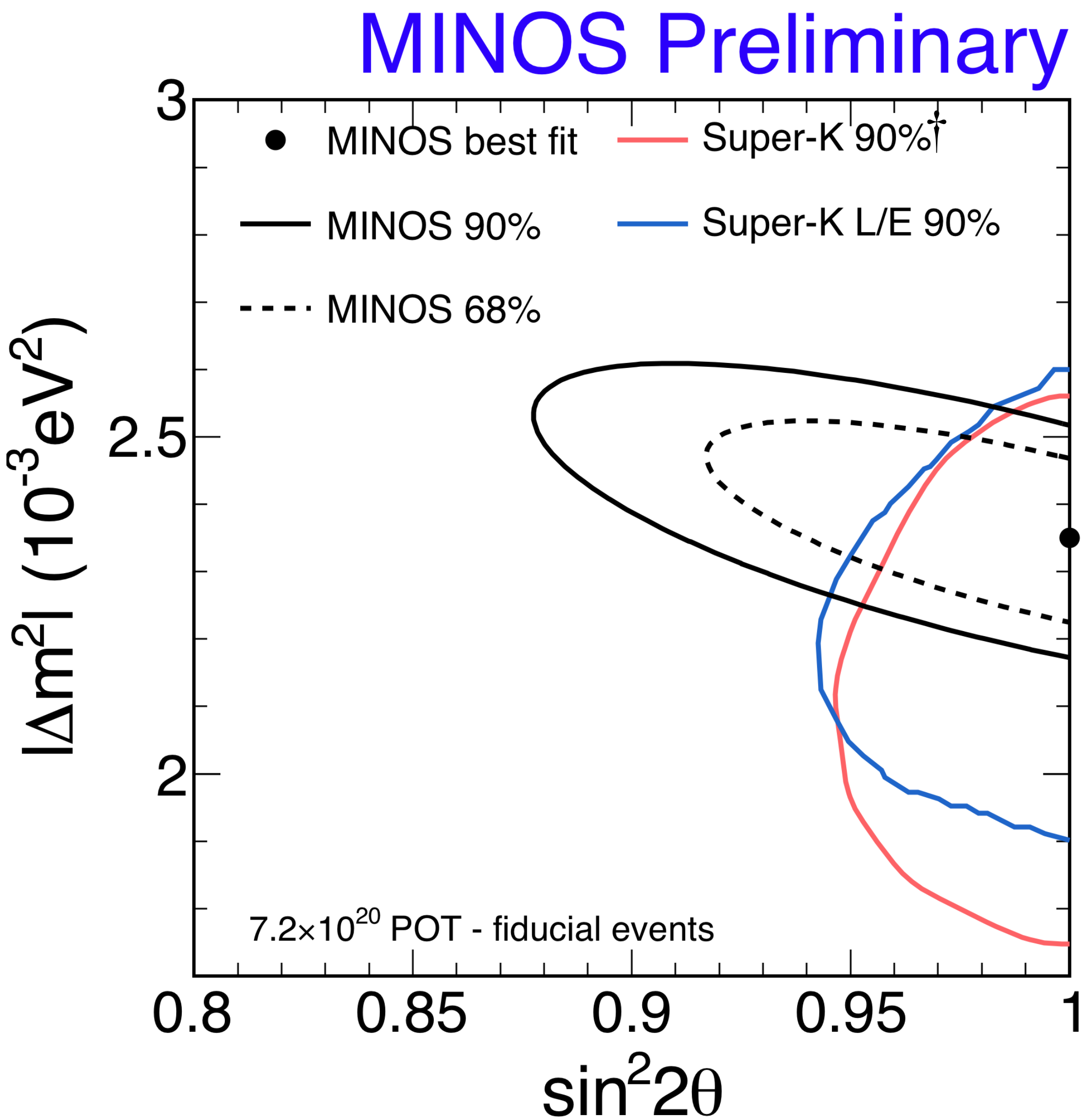


$$\left|\Delta m^2_{\mathrm{atm}}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2(2\theta_{23}) = 1$$

$$\sin^2(2\theta_{23}) > 0.91\ (90\%\ \mathrm{C.L.})$$

Neutrino Contour



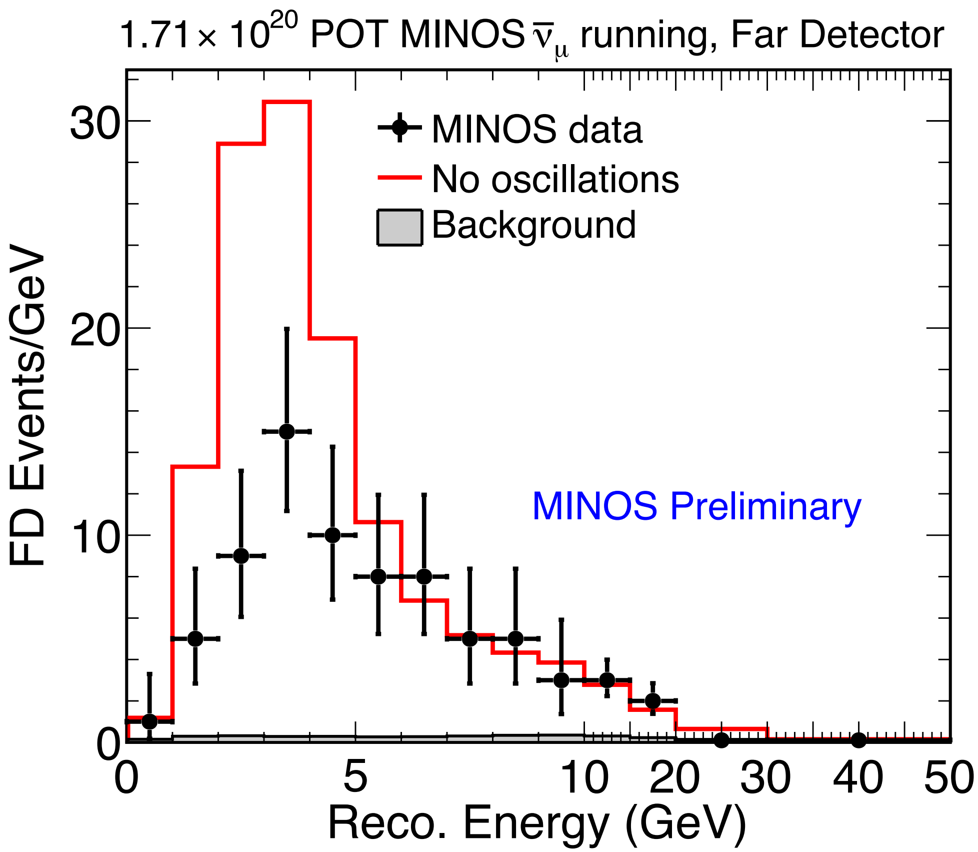
$$\left|\Delta m^2_{atm}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2(2\theta_{23}) = 1$$

$$\sin^2(2\theta_{23}) > 0.91\ (90\%\ \mathrm{C.L.})$$

†Super-Kamiokande Collaboration (preliminary)

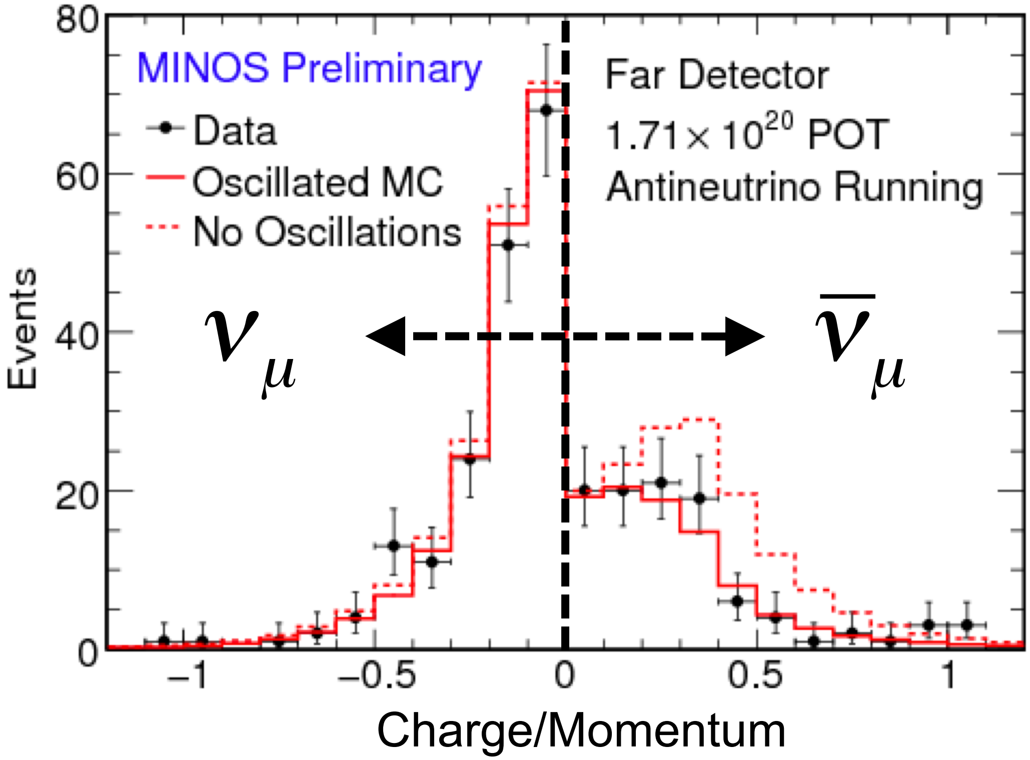
Far Detector Antineutrino Data

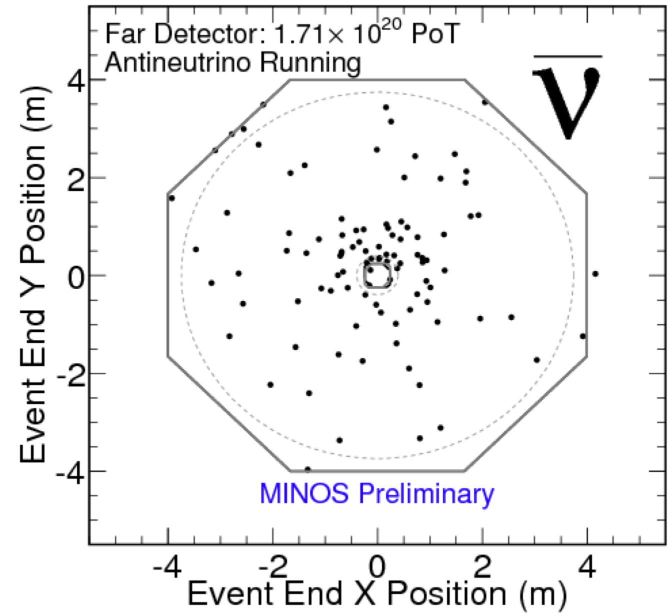


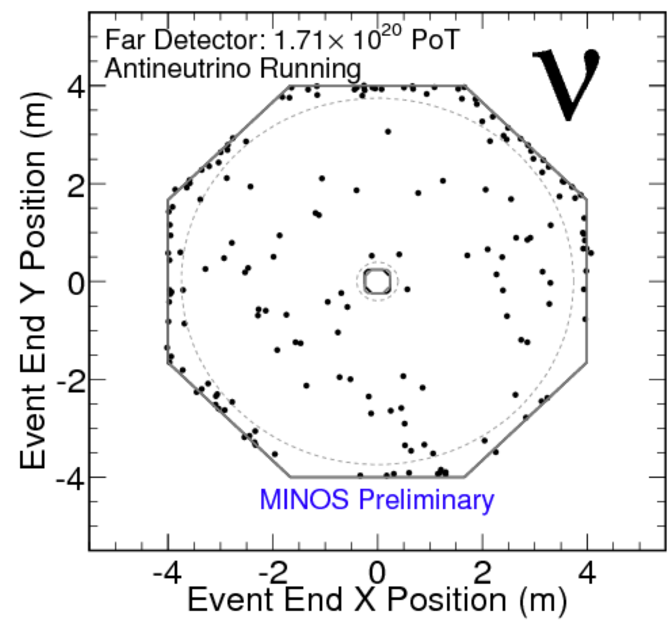
➔**155** expected without oscillations

➔ **97** observed events

Far Detector Data

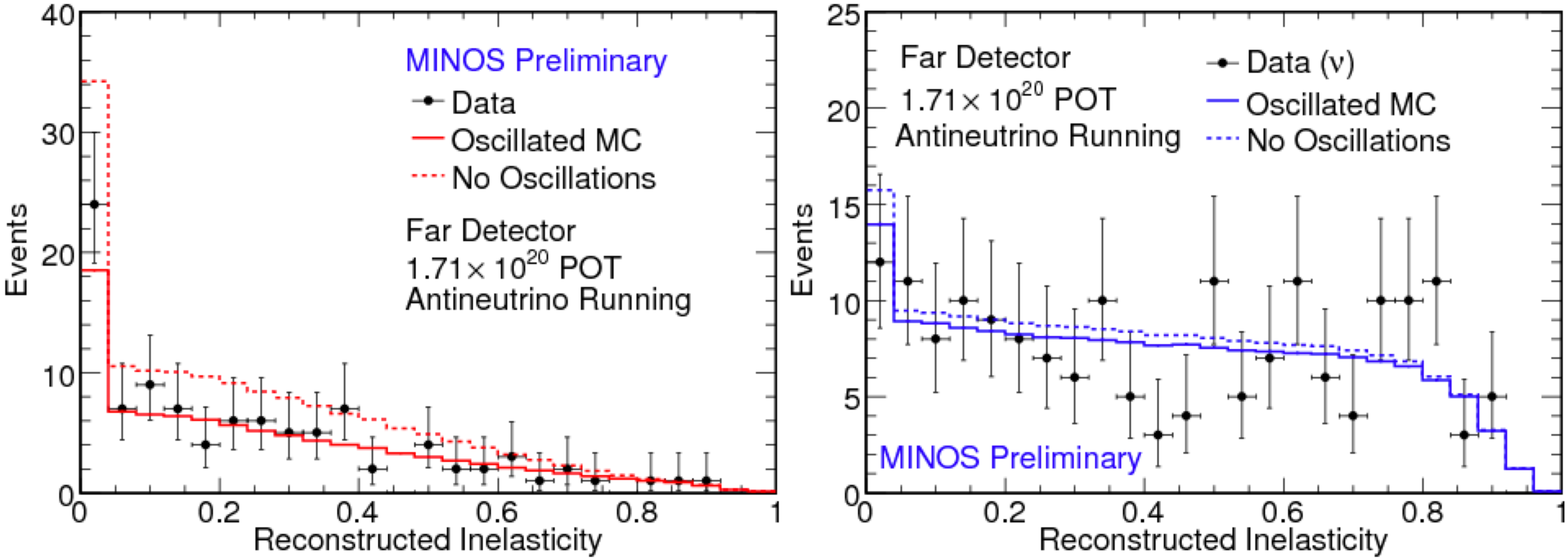






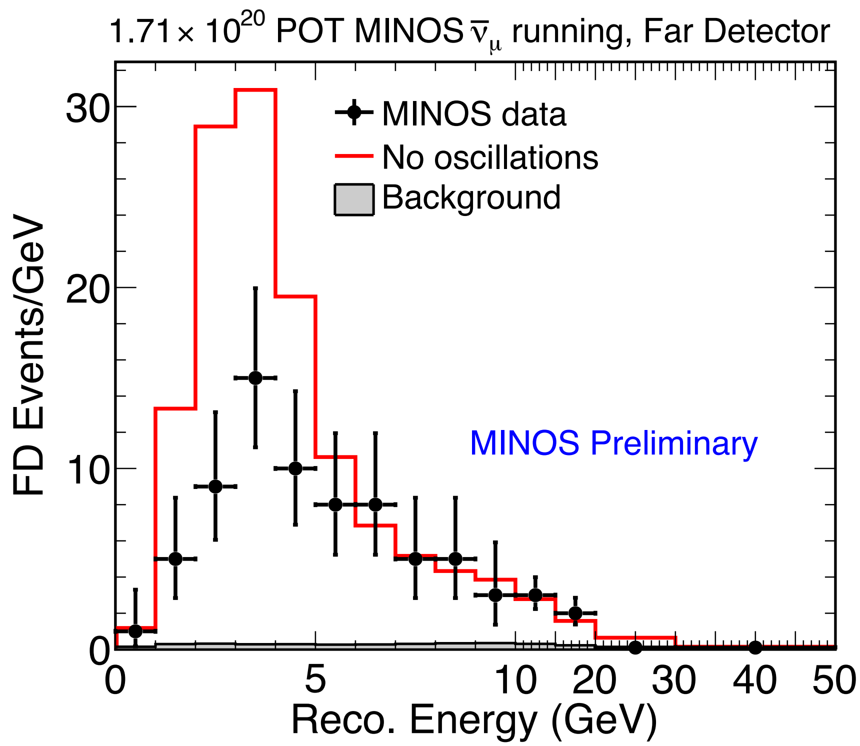
- Good data/mc agreement in charge/momentum
- Antineutrinos focused inwards
- Neutrinos defocused outwards

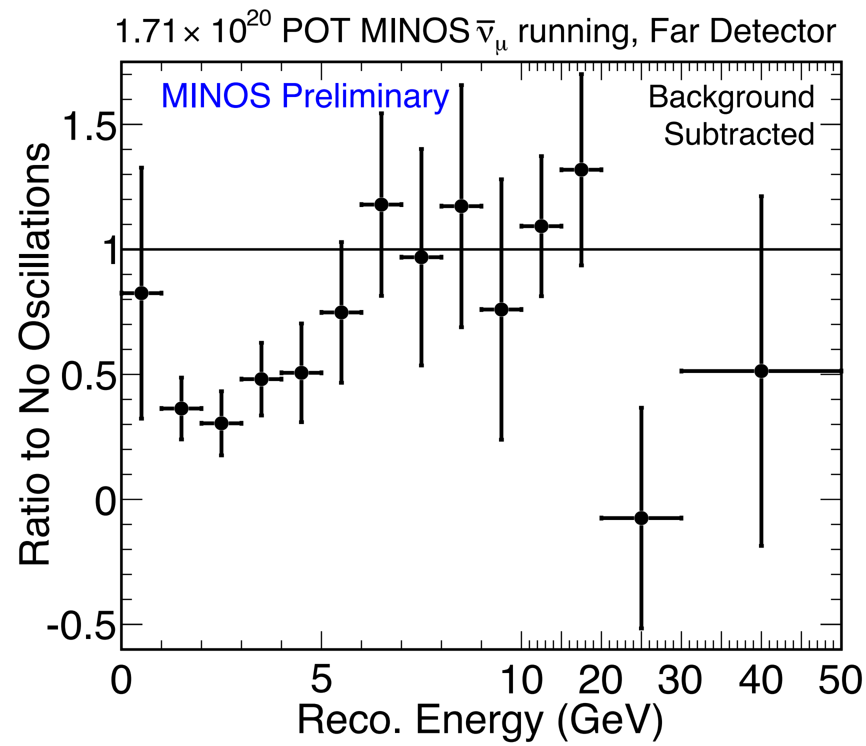
Far Detector Data



- Data shows the expected distributions of hadronic energy fraction for both neutrinos and antineutrinos

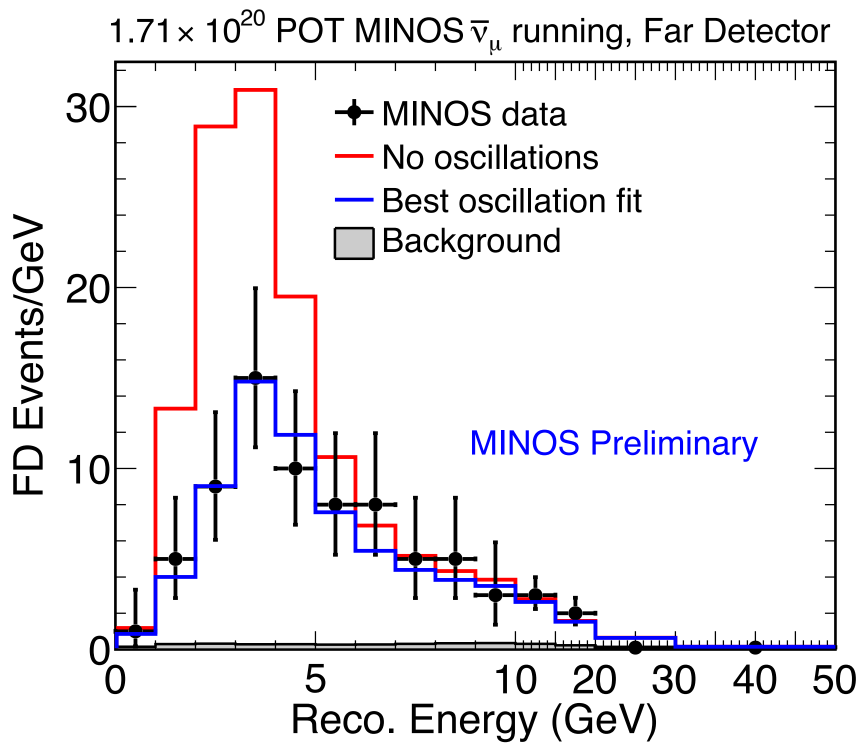
Far Detector Antineutrino Data

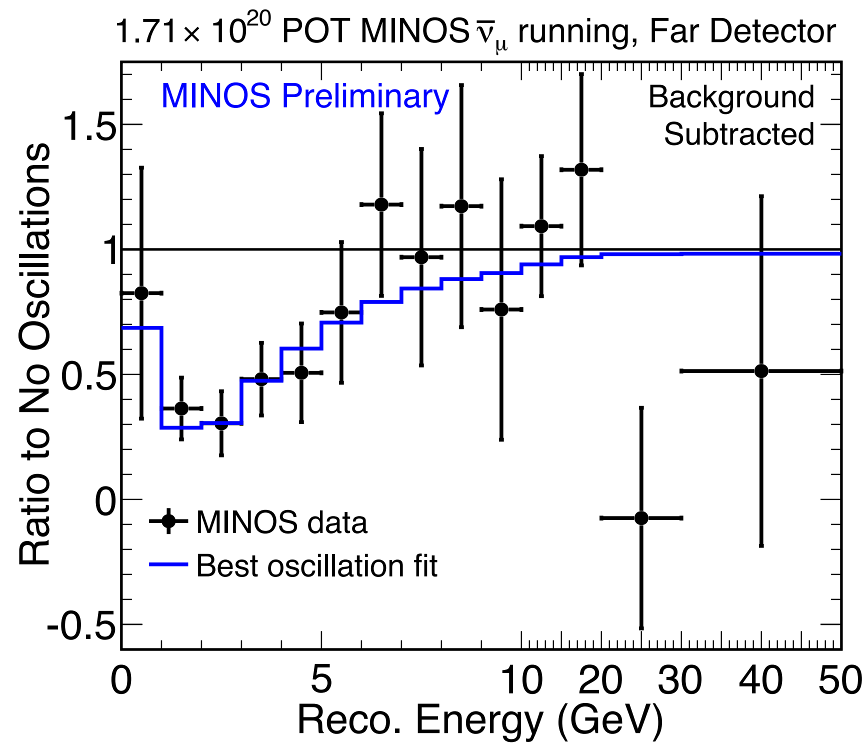




- **155** expected without oscillations
- **97** observed events

Far Detector Antineutrino Data





➔ **155** expected without oscillations

➔ **97** observed events

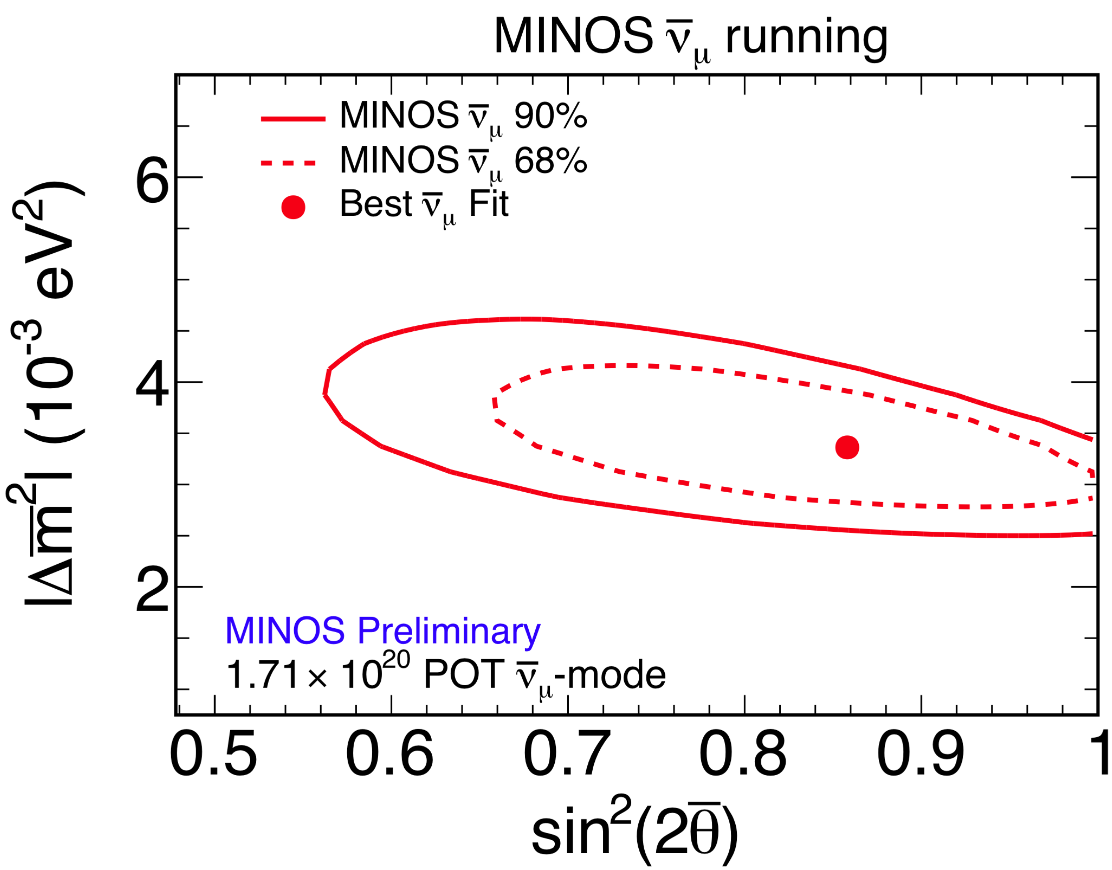
No-oscillations hypothesis is disfavored at **6.3σ**

Antineutrino Contour

$$\left|\Delta \overline{m}^2_{\text{atm}}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \text{eV}^2$$

$$\sin^2\left(2\overline{\theta}_{23}\right) = 0.86 \pm 0.11$$

- Contour is determined using Feldman-Cousins.
  - Includes systematics



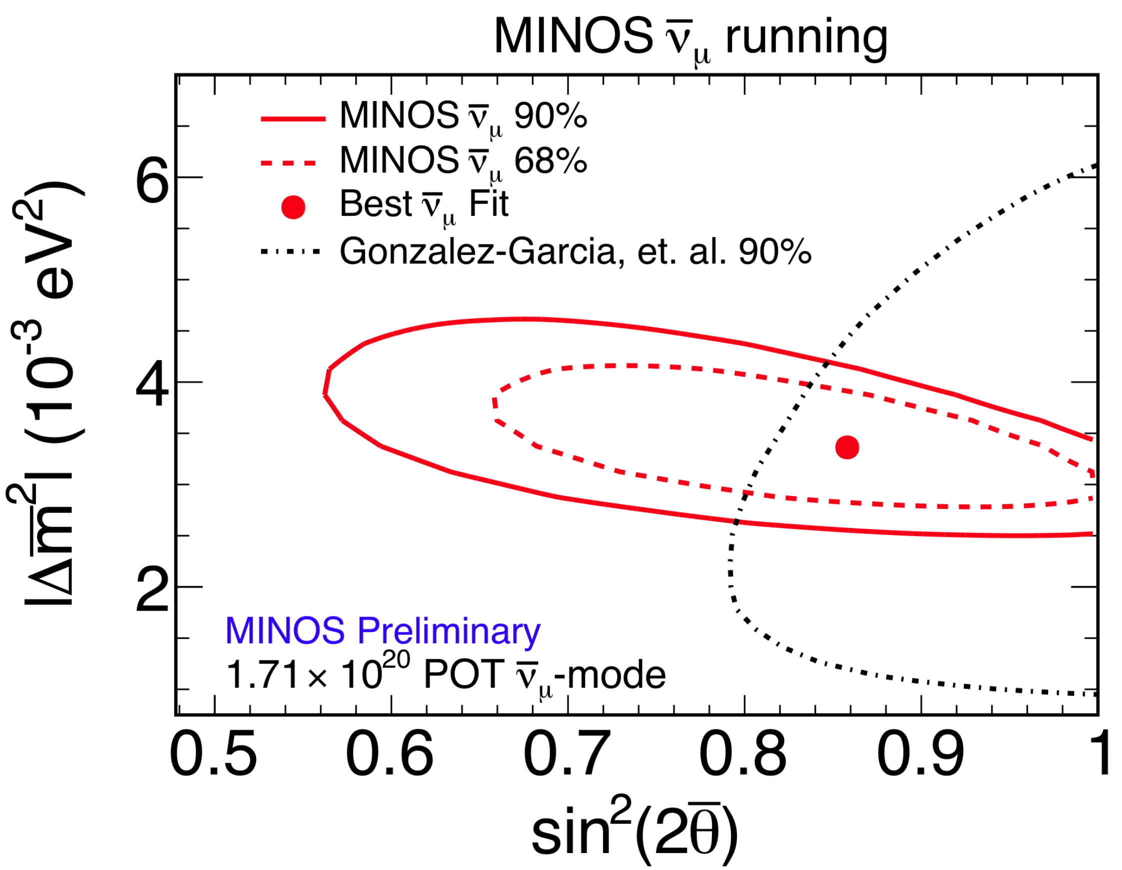
Antineutrino Contour

$$\left|\Delta \overline{m}^2_{\mathrm{atm}}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \mathrm{eV}^2$$

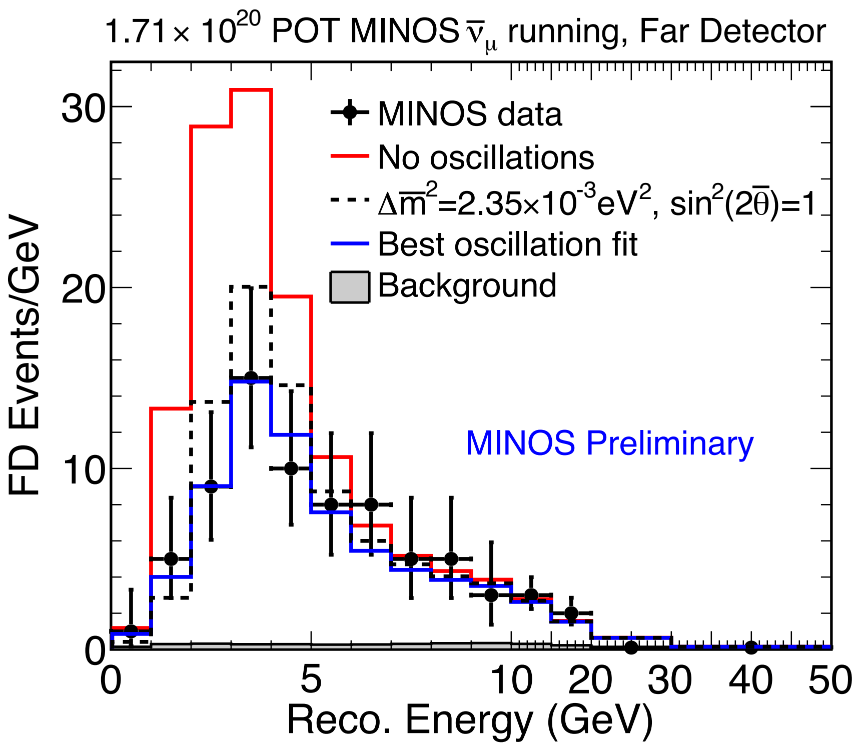
$$\sin^2\left(2\overline{\theta}_{23}\right) = 0.86 \pm 0.11$$

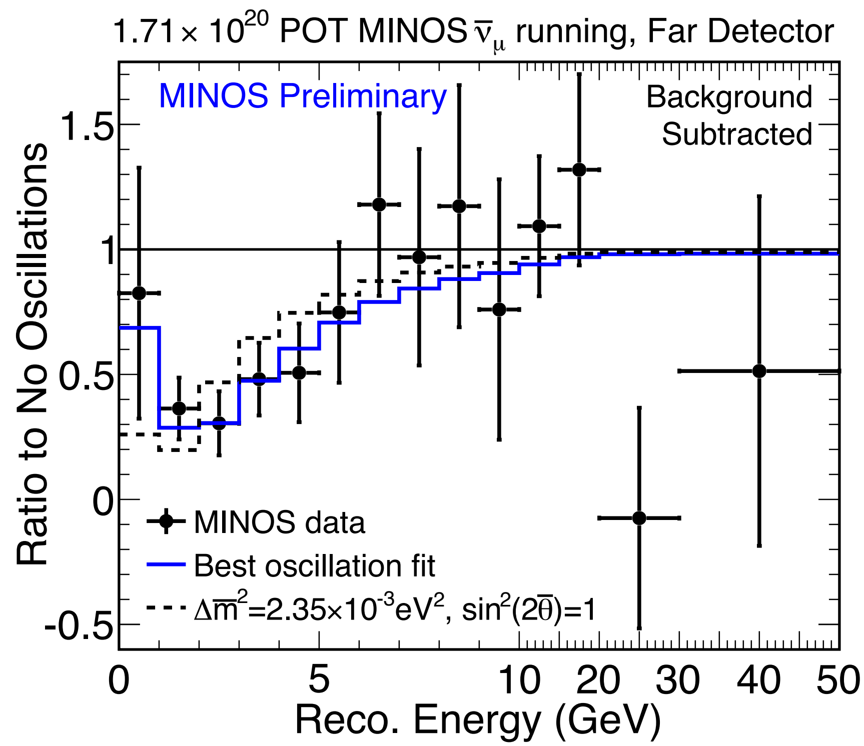
- Contour is determined using Feldman-Cousins.
  - Includes systematics
- Dot-dash line is a fit to all non-MINOS data

M.C. Gonzalez-Garcia and M. Maltoni Phys. Rept. 460, 2008



Comparison to Neutrinos





- Dashed line shows the antineutrino prediction at the neutrino best fit point.

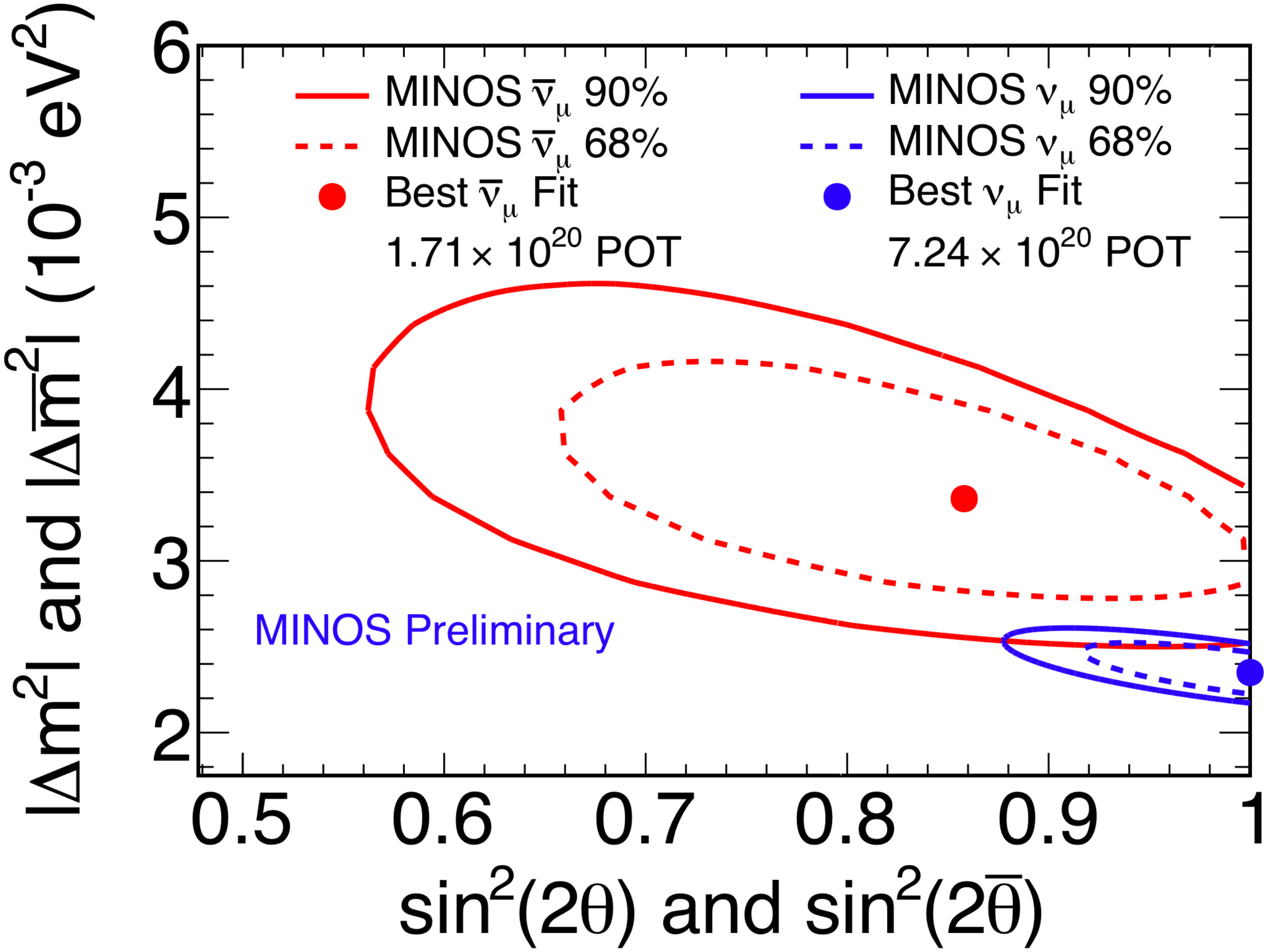
Neutrinos and Antineutrinos

$$\left|\Delta \overline{m}^2_{\rm atm}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ {\rm eV}^2$$

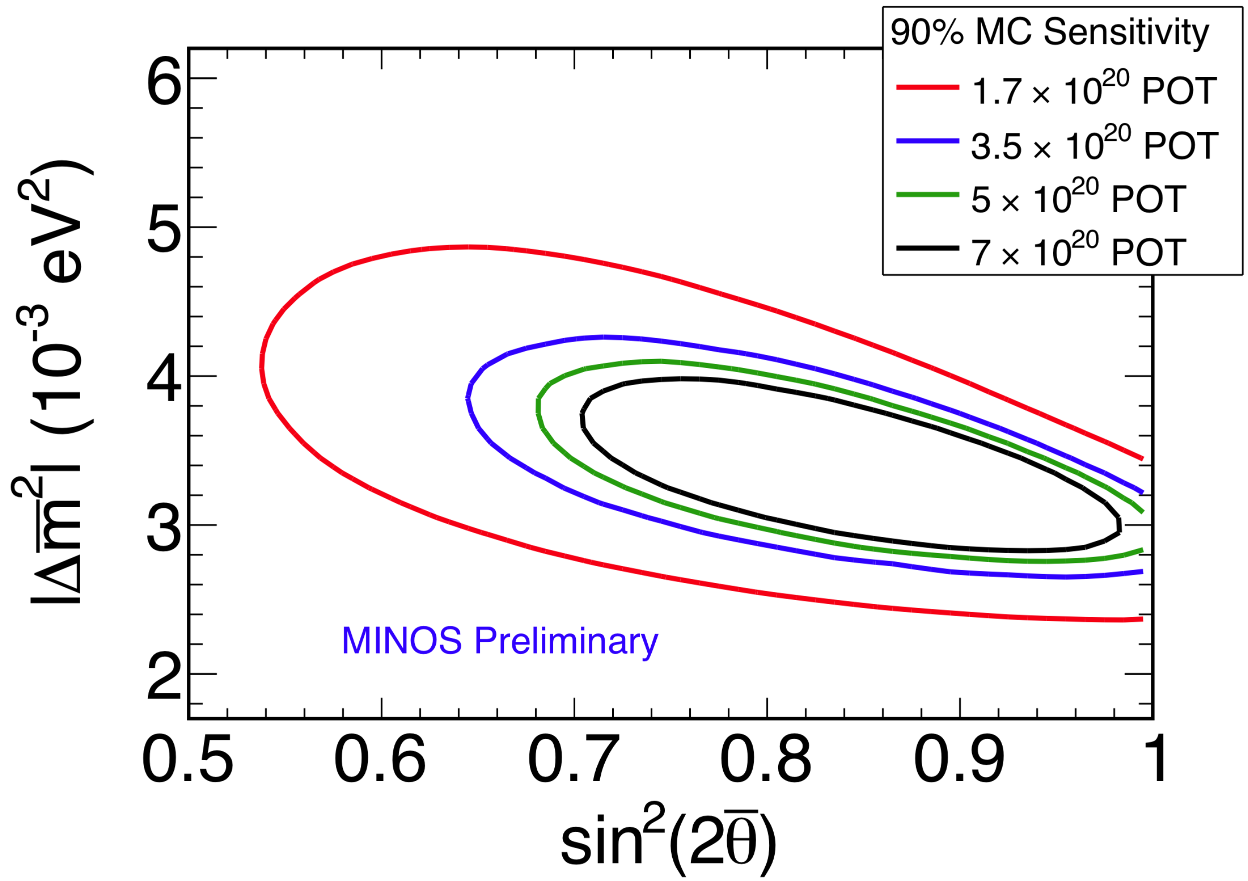
$$\sin^2\left(2\overline{\theta}_{23}\right) = 0.86 \pm 0.11$$

$$\left|\Delta m^2_{\rm atm}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ {\rm eV}^2$$

$$\sin^2\left(2\theta_{23}\right) > 0.91\ (90\%\ {\rm C.L.})$$



With More Antineutrinos...



- Even just another 4.5 months of running (double the current data set) would decrease the error by ~30%.

Conclusions

- MINOS has the most precise measurement of $|\Delta m^2_{atm}|$
- MINOS has the first direct, precision measurement $|\Delta \overline{m}^2_{atm}|$

$$\left|\Delta m^2_{\mathrm{atm}}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(2\theta_{23}) > 0.91 \text{ (at 90\%)}$$

$$\left|\Delta \overline{m}^2_{\mathrm{atm}}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2(2\overline{\theta}_{23}) = 0.86 \pm 0.11$$

- Measured with double the neutrino data and a dedicated antineutrino run
- With more antineutrino beam we can rapidly improve the precision on the antineutrino oscillation parameters

Acknowledgements

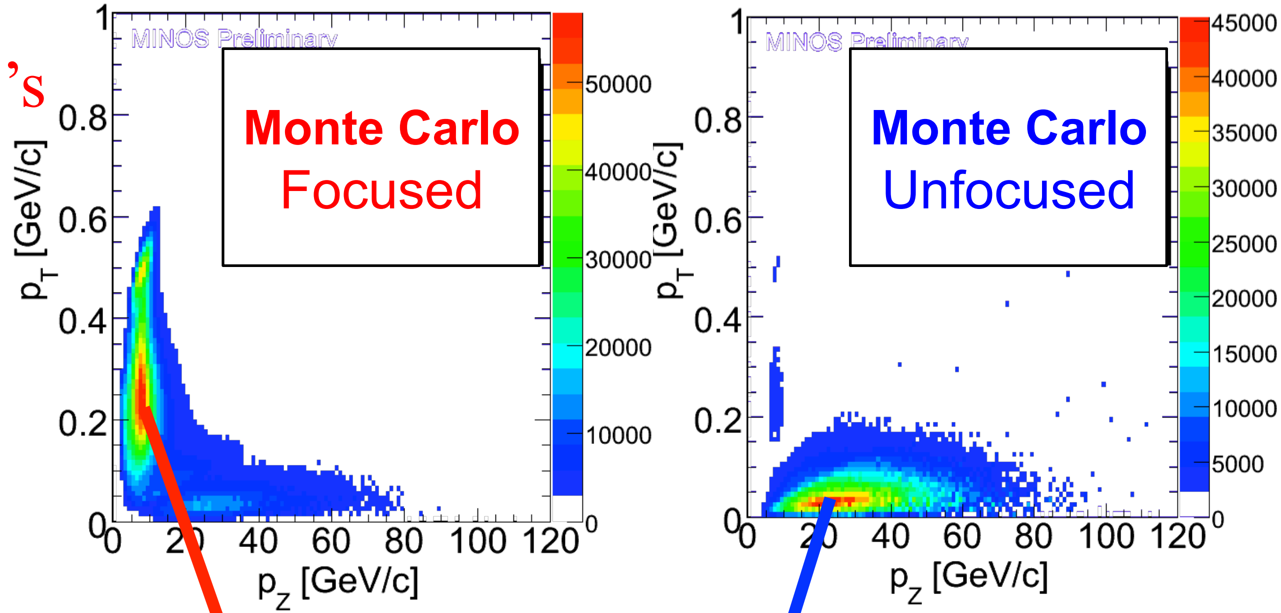
- On behalf of the MINOS Collaboration, I would like to express our gratitude to the many Fermilab groups who provided technical expertise and support in the design, construction, installation and operation of the experiment

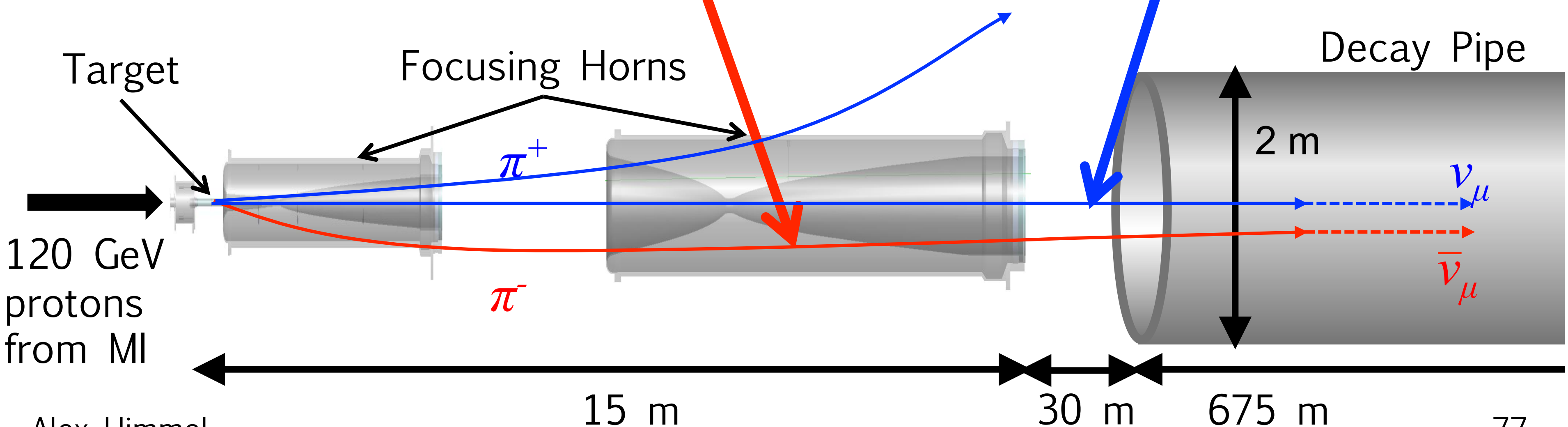
- We also wish to thank the crew at the Soudan Underground Laboratory for keeping the Far Detector running so well

- We also gratefully acknowledge financial support from DOE, STFC(UK), NSF and thank the University of Minnesota and the Minnesota DNR for hosting us

Peak vs. Tail

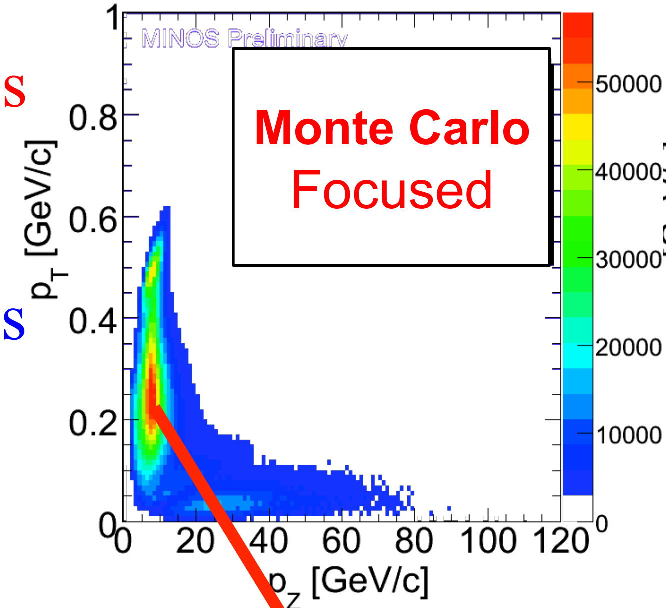
- $\bar{\nu}_\mu$'s from **high-p_t** π^-'s
  - Focused by horns
- ν_μ's from **low-p_t** π^+'s
  - Pass through horn center

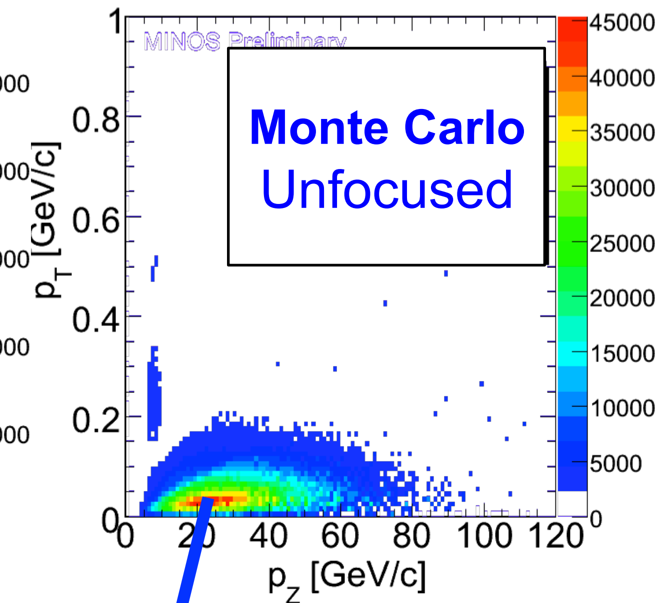


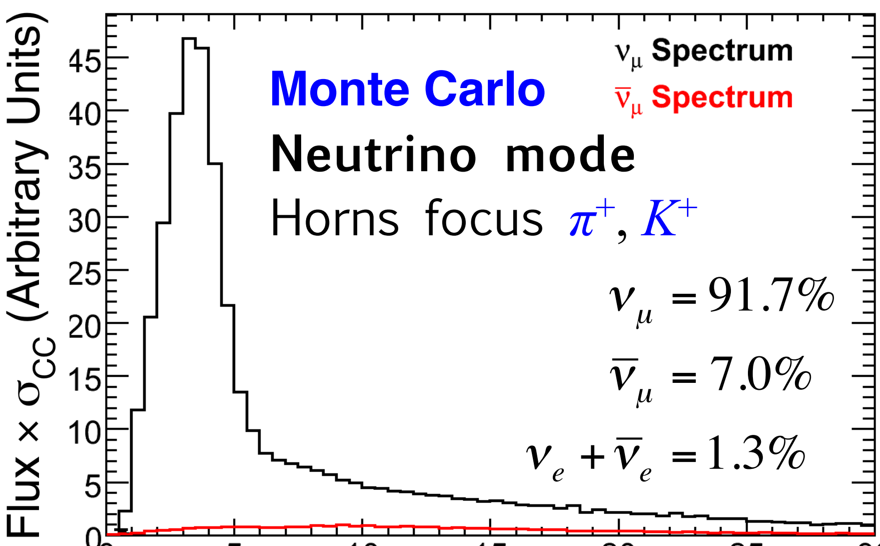


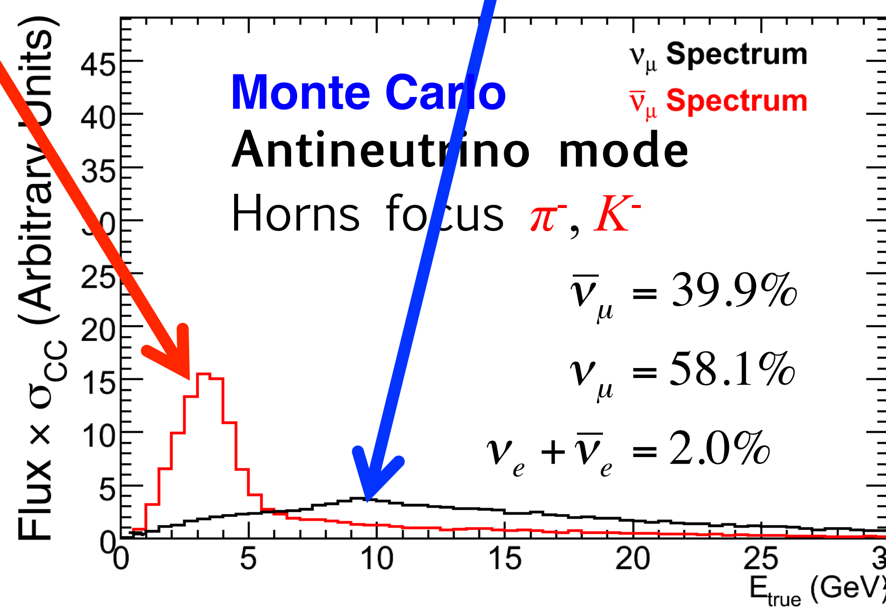
Peak vs. Tail

- $\bar{\nu}_\mu$'s from **low-p_t** π^-'s
  - Focused by horns
- ν_μ's from **high-p_t** π^+'s
  - Pass through horn center







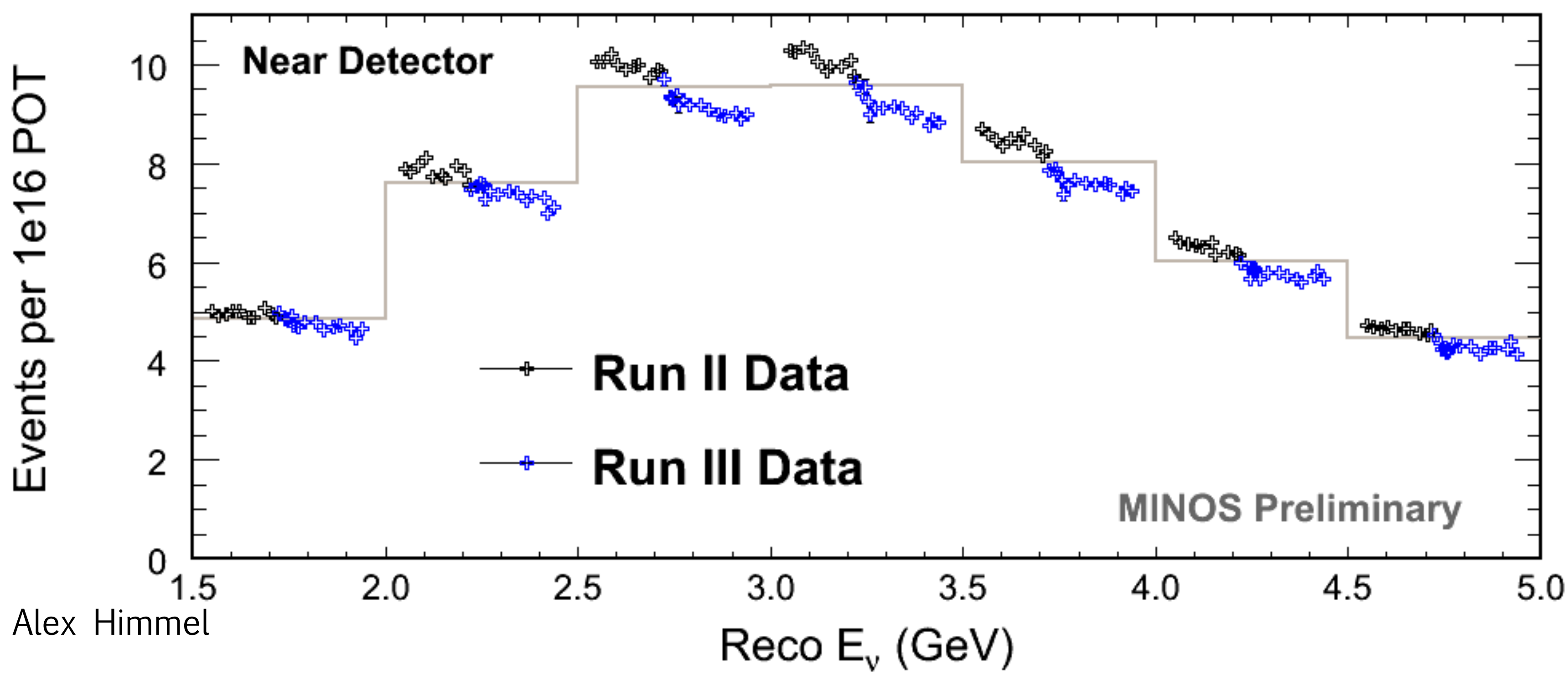


Helium in the Decay Pipe

- At the beginning of Run III, helium was added to the decay pipe to prevent failure of the upstream window.
  - Our previous flux simulation could not model the helium using GFLUKA as part of GEANT3
  - Replaced it with a new flux simulation that is all FLUKA which accurately predicts the effects of helium.

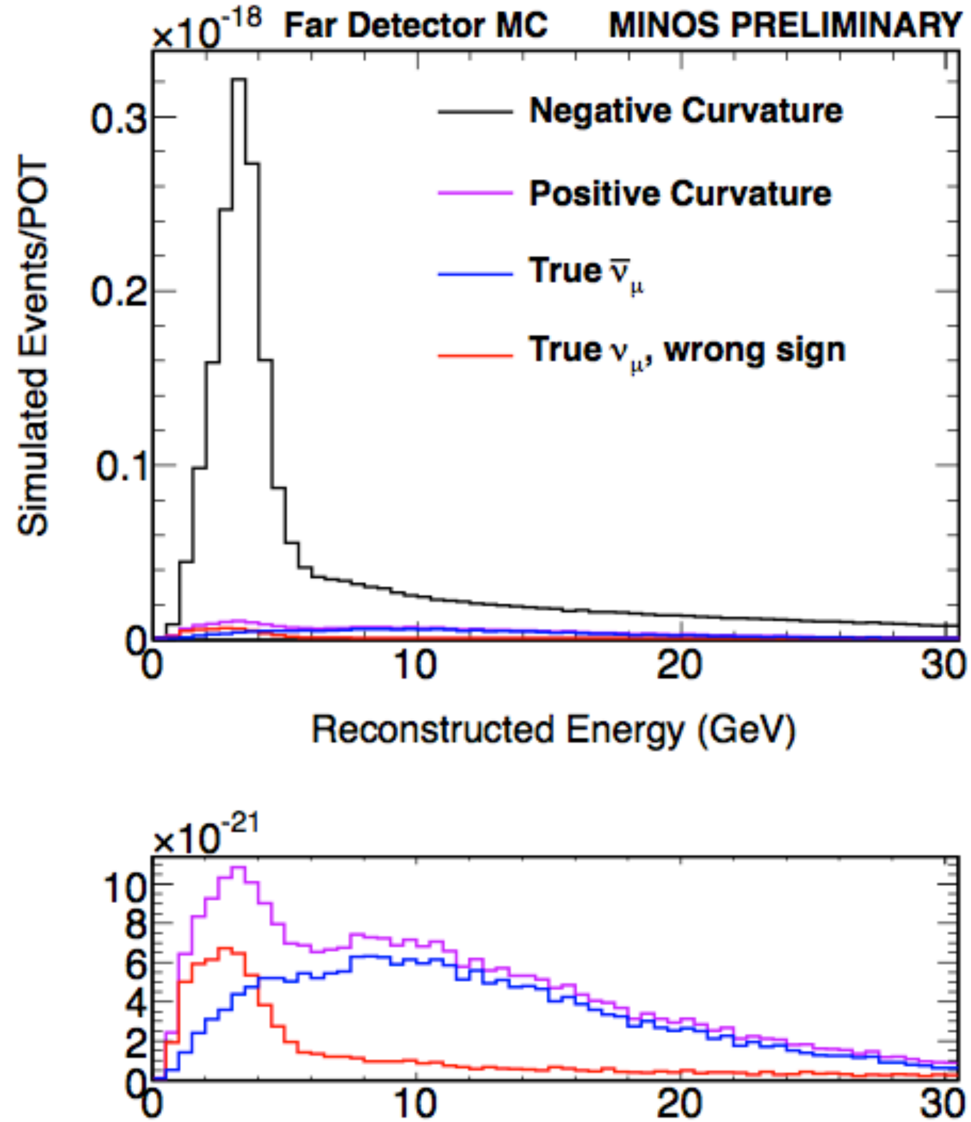
Target Degradation

- Began during Run II and continued through Run III
- The exact mechanism of the decay is not known
- Missing fins at the shower max in the target model the energy-dependent effect
- Target to undergo post-mortem later this year
- Cancels between the two detector

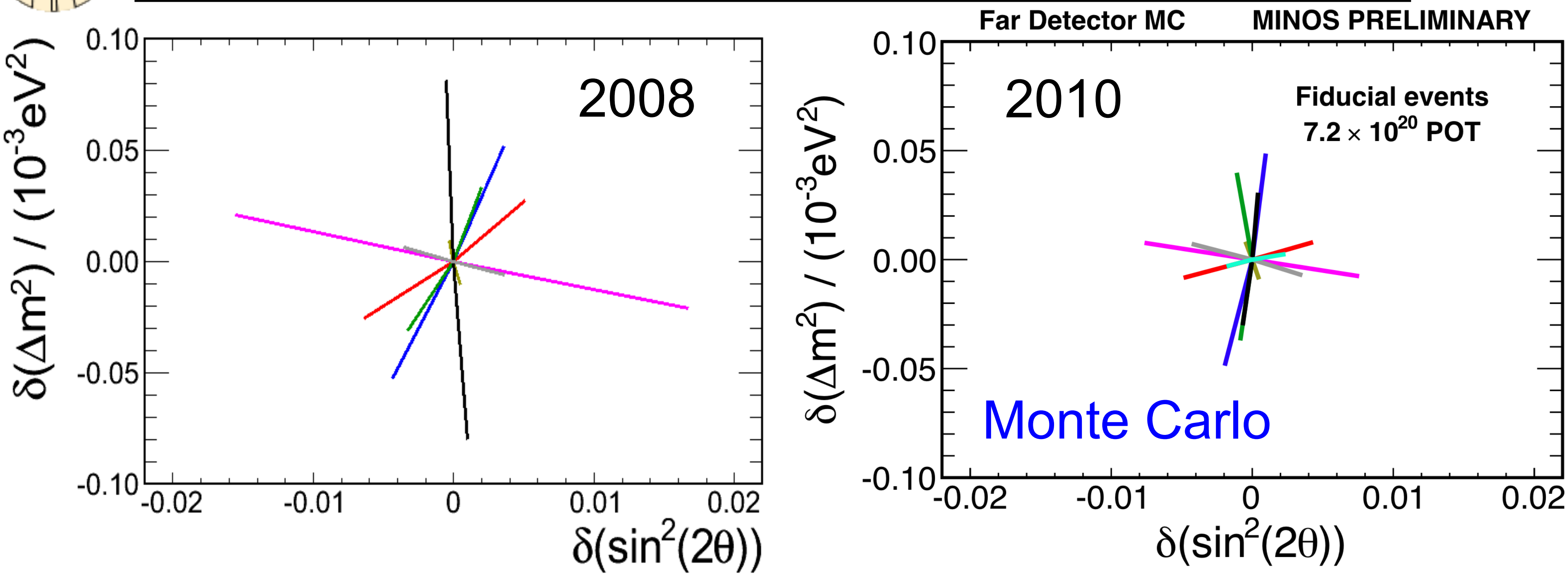


Removing the Charge Cut

- The positive-curvature sample is ~30% true CC neutrinos.
- If the antineutrinos are oscillated at the antineutrino best fit point, makes a change only in 3rd significant digit of the result.

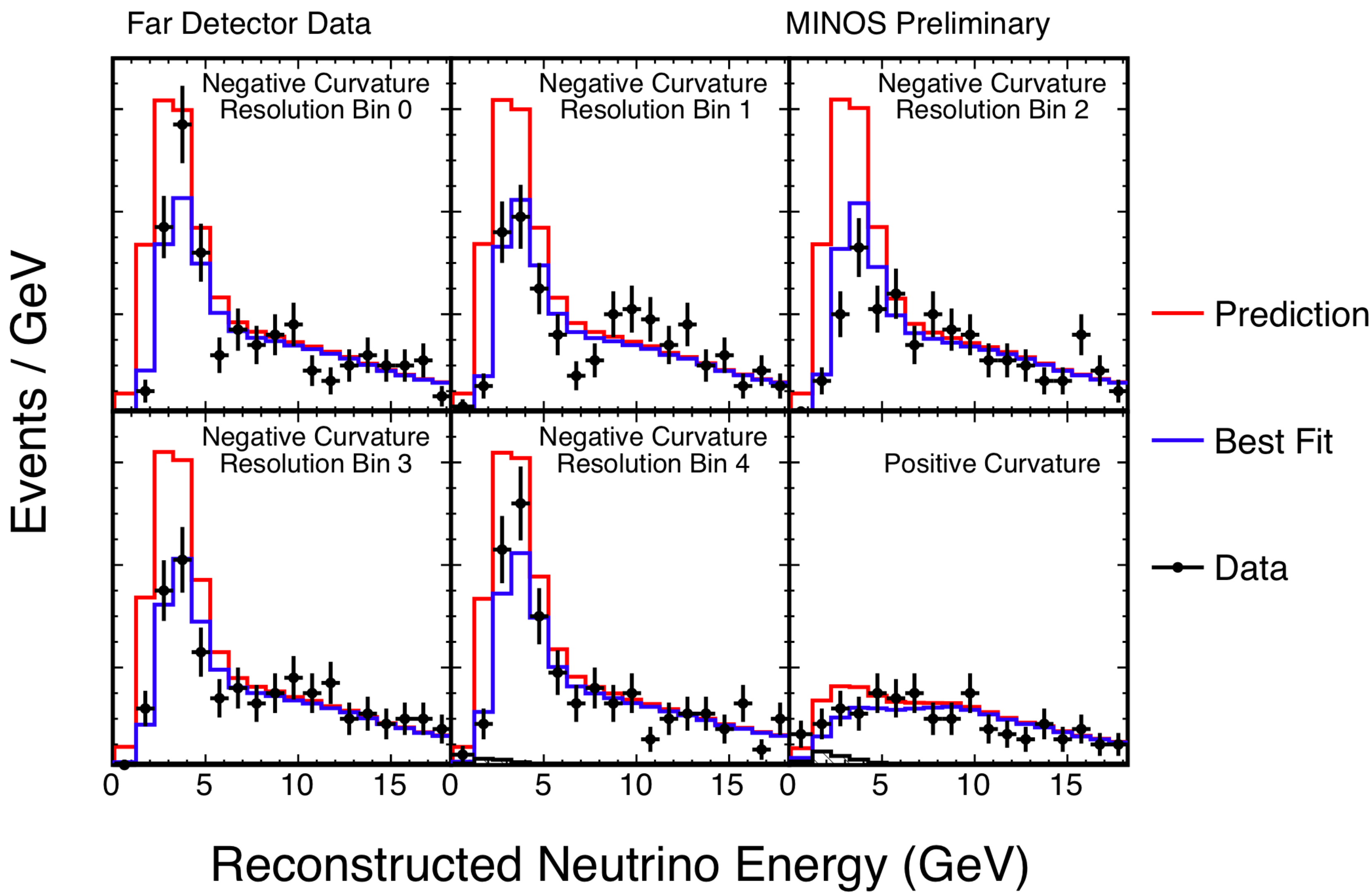


Change in Systematics

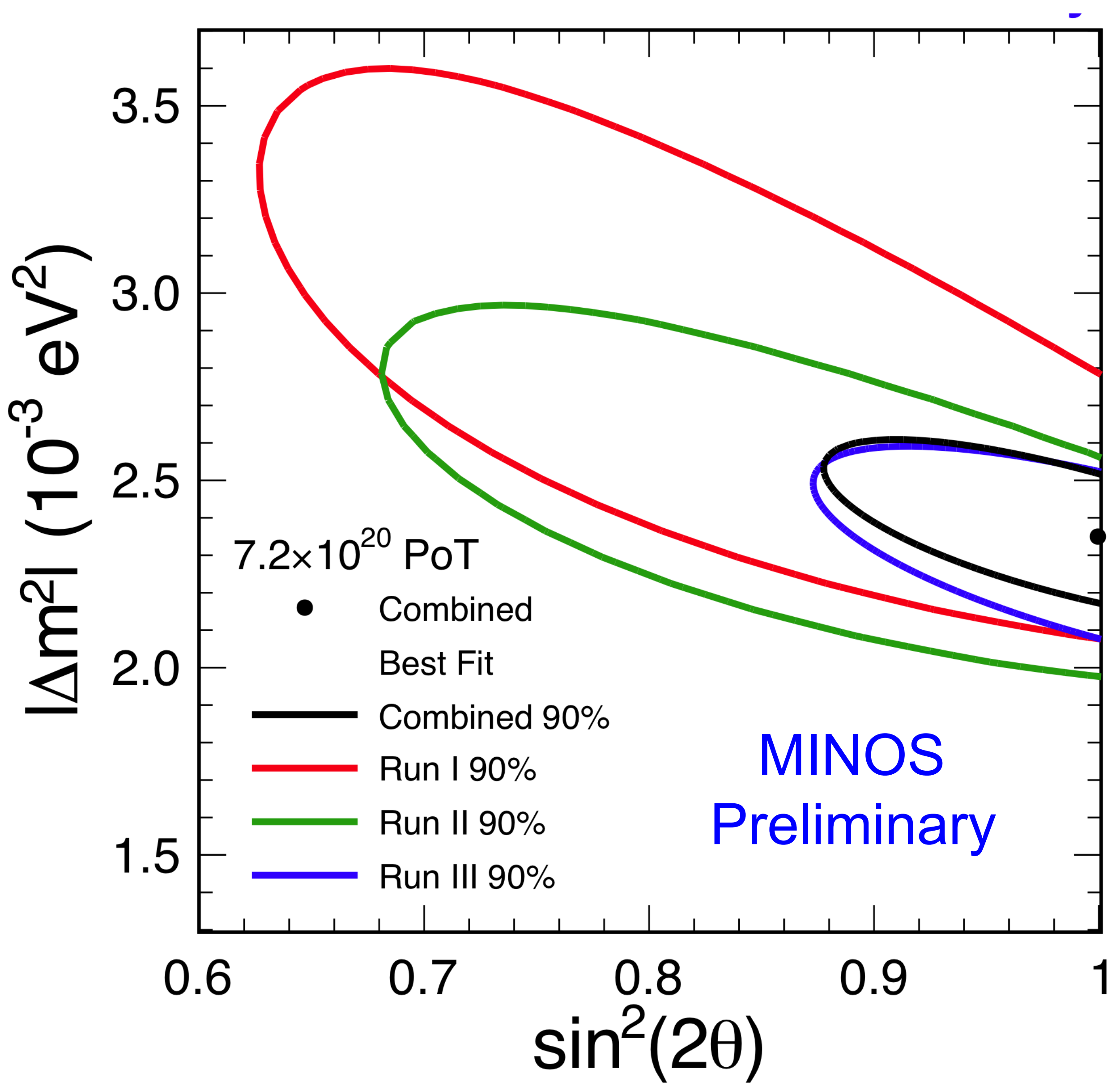


- Overall hadronic energy
- Track energy
- NC background
- Relative normalisation
- Relative hadronic energy
- Cross sections
- Charge mis-ID
- Beam

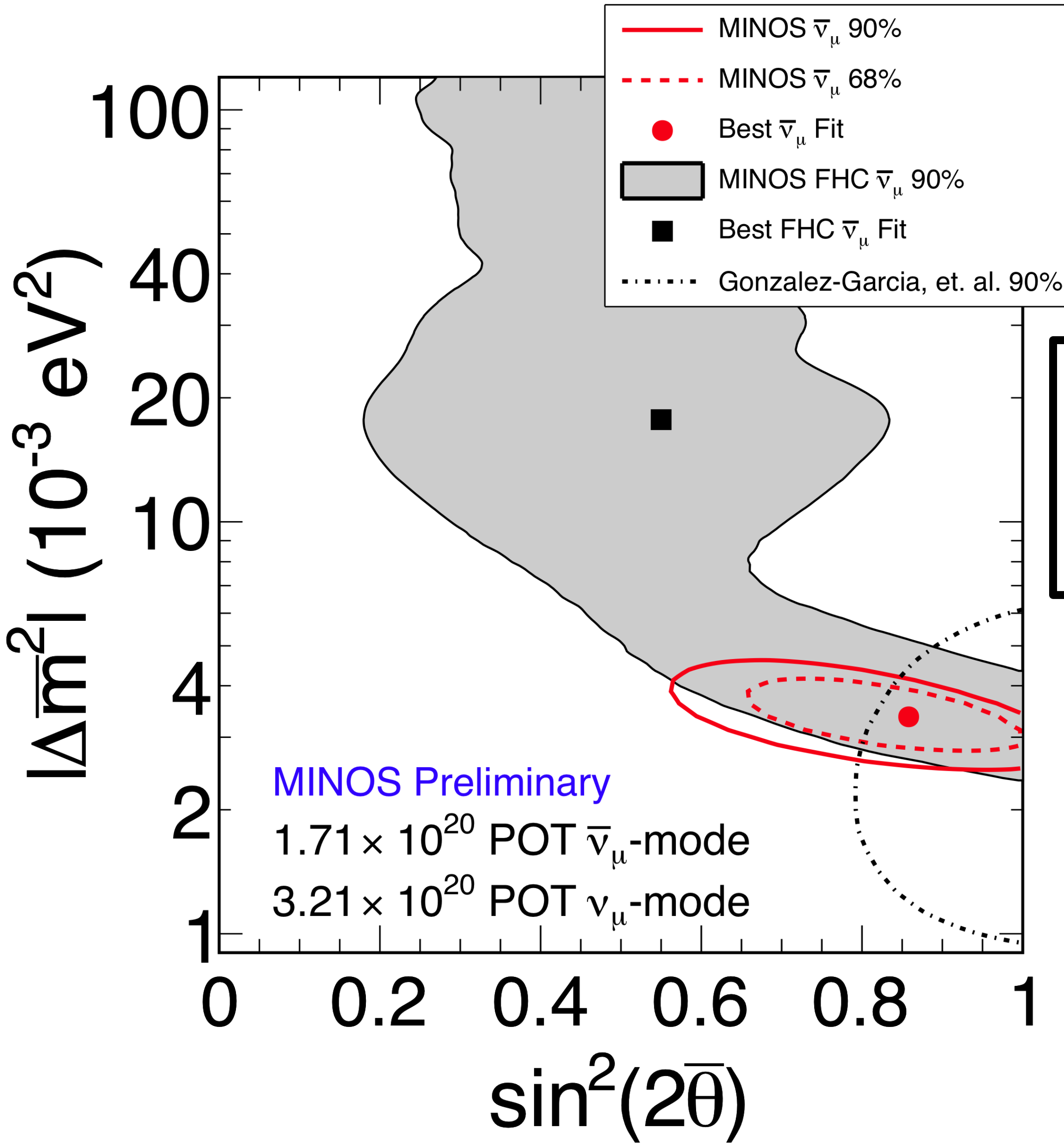
Neutrino Spectrum



Neutrino Contour by Run



Antineutrino Contour

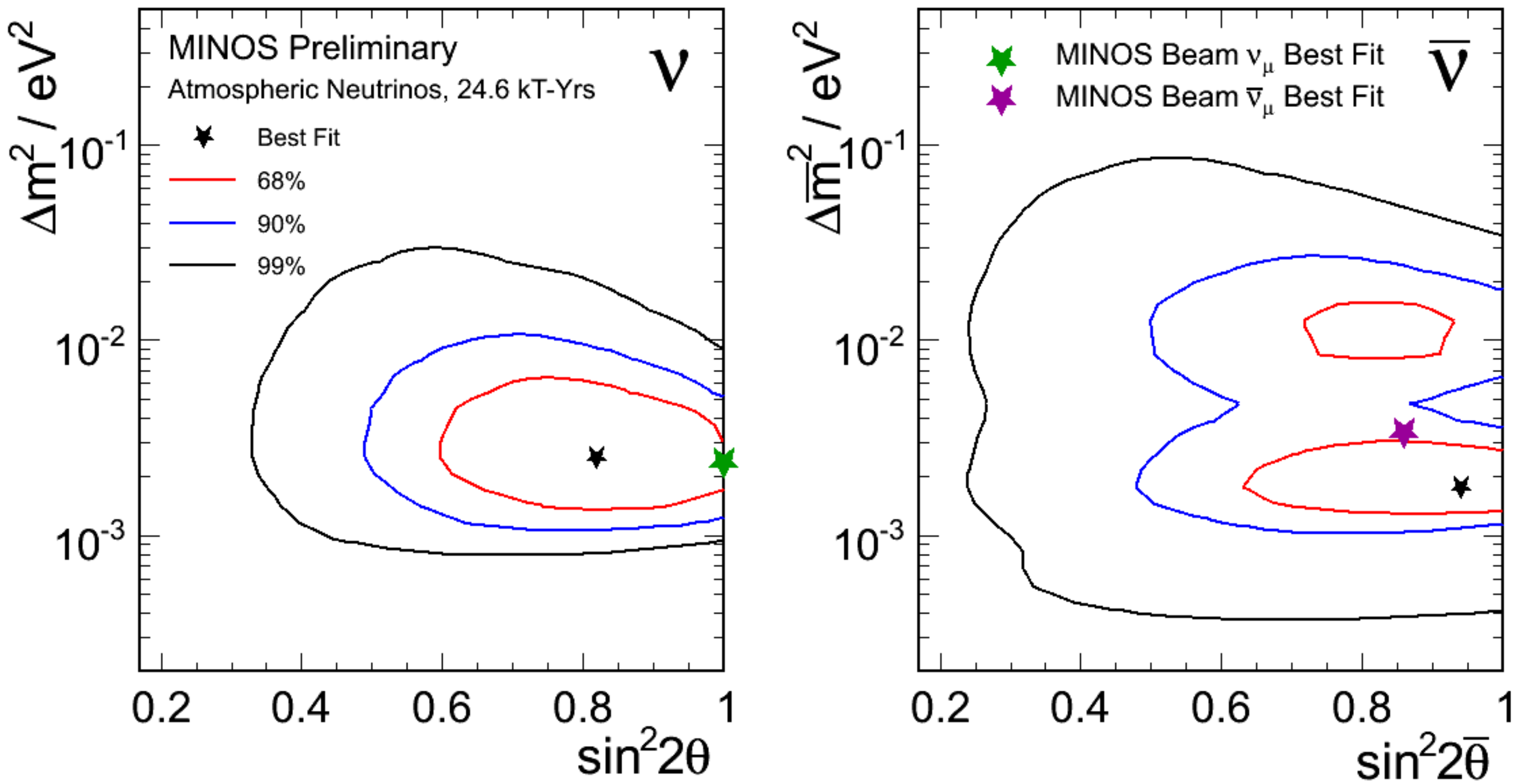


$$\left|\Delta\bar{m}^2_{\mathrm{atm}}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\left(2\bar{\theta}_{23}\right) = 0.86 \pm 0.11$$

A combined analysis using all antineutrino data is planned.

Atmospheric Neutrinos



$$R^{data}_{\bar{\nu}/\nu} \,/\, R^{MC}_{\bar{\nu}/\nu} = 1.04^{+0.11}_{-0.10} \pm 0.10$$

$$\left|\Delta m^2\right| - \left|\overline{\Delta m^2}\right| = 0.4^{+2.5}_{-1.2} \times 10^{-3}\,\mathrm{eV}^2$$